

**Project Report
ATC-337a**

Aircraft Derived Data Validation Algorithms

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6 August 2012

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EXECUTIVE SUMMARY

This document replaces ATC-337 [1].

US Military aircraft operating in civilian airspace are subject to the same avionics equipage requirements as civilian aircraft. To satisfy Air Traffic Control (ATC) mandates, aircraft flying in civilian airspace must be equipped with a Mode S Secondary Surveillance Radar (SSR) transponder that can provide aircraft-derived data when requested by a Mode S SSR. Equipage with a Mode S transponder and the reporting of aircraft call sign is referred to as Elementary Surveillance (ELS). The reporting of aircraft intent and state data is referred to as Enhanced Surveillance (EHS). To meet the European requirements of ELS and EHS, current aircraft data must be maintained in the transponder and provided at the request of a Mode S ground interrogator. These data are used by ATC ground automation systems to provide better predictions of near-term aircraft trajectories than could be obtained from traditional surveillance data, thereby enabling more efficient use of crowded airspace.

The United States Air Force (USAF) tasked Lincoln Laboratory to validate that Mode S EHS data from US Military aircraft are in compliance with European mandates. Analysis of US Military aircraft EHS data can be used to identify US Military aircraft with potential compliance shortfalls with respect to the European mandates. This report provides details of the algorithms developed by Lincoln Laboratory to perform this analysis.

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1. INTRODUCTION

US Military aircraft flying in civilian airspace are subject to the same avionics equipage requirements as civilian aircraft. The United States Air Force (USAF) tasked Lincoln Laboratory to validate that Mode S Enhanced Surveillance (EHS) data from US Military aircraft are in compliance with European mandates. Analysis of the US Military aircraft EHS data can identify US Military aircraft with potential compliance shortfalls with respect to the European mandates. This report provides details of the algorithms developed by Lincoln Laboratory to perform this analysis. In Section 2, a brief overview of radar surveillance methods and history is provided.

To satisfy European Air Traffic Control (ATC) mandates, aircraft flying in their airspace must be equipped with Mode S transponders that can provide aircraft derived data when requested by a Mode S Secondary Surveillance Radar (SSR), discussed further in Section 3. Equipage with a Mode S transponder and the reporting of aircraft call sign is referred to as Elementary Surveillance (ELS). The reporting of aircraft intent and state data is referred to as EHS. To meet the requirements of ELS and EHS, current aircraft data must be maintained in the transponder and provided at the request of a Mode S SSR. These data are used by ATC ground automation systems to provide better predictions of near-term aircraft trajectories than could be obtained from traditional surveillance data, thereby enabling more efficient use of crowded airspace.

Aircraft data sent from a Mode S transponder are referred to as Downlinked Aircraft Parameters (DAPs). Validation of DAPs is performed by comparing downlinked data with an estimate of the data derived from other data sources (e.g., SSR derived azimuth). Surveillance smoothing (Section 5) and wind estimation (Section 6) are an integral part of DAP validation. This report introduces a newly developed wind estimation method and describes its value in the validation process. The validation process (Section 7) is then applied to ground speed, true track angle, track angle rate, roll angle, magnetic heading, and true airspeed. These aircraft parameters are available via Registers 50₁₆ and 60₁₆ and are described in Figure 1.1. The results of these validation processes are condensed and made available to the end user for review. There are two main reports, the Aircraft Specific Validation Report (ASVR) and Cross Track Report (XTR). The ASVR provides information on the DAPs of a specific aircraft track. Since there are many ASVRs produced on a daily basis, the XTR provides an overview of all tracks over a given time period, greatly reducing the workload of the end user. These reports are discussed in Section 8.

We summarize with a discussion of the current added value of the system in Section 9 and a discussion of planned future work in Section 10.

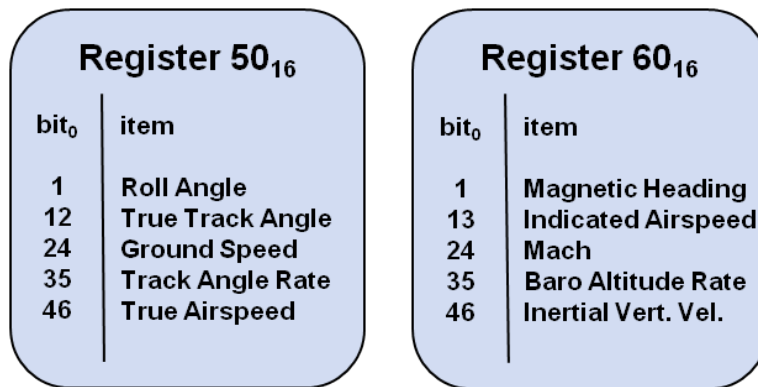


Figure 1.1. Register 50₁₆ (Track and Turn Report) and 60₁₆ (Heading and Speed Report) layouts. Each parameter begins at the bit specified above and contains a single status bit and sign bit, followed by magnitude. Registers have a length of 56 bits.

2. RADAR SURVEILLANCE BACKGROUND

Air Traffic Control (ATC) uses radar to locate aircraft in order to display their position on screens. Radars rotate approximately every 5 seconds for Terminal Area radars and 12 seconds for En Route radars. Surveillance updates are provided to the controllers for each radar sweep. There are two types of aircraft surveillance radar:

1. Primary Surveillance Radar (PSR), which uses energy reflected off an aircraft body to determine slant range and azimuth; and
2. Secondary Surveillance Radar (SSR), which interrogates the aircraft's transponder to obtain additional useful information about the aircraft. A transponder is a small electronic device located on the aircraft, and has a cockpit control panel that the pilot uses to enter data. It communicates with the SSR through a small exterior antenna. It communicates with the SSR through a small exterior antenna.

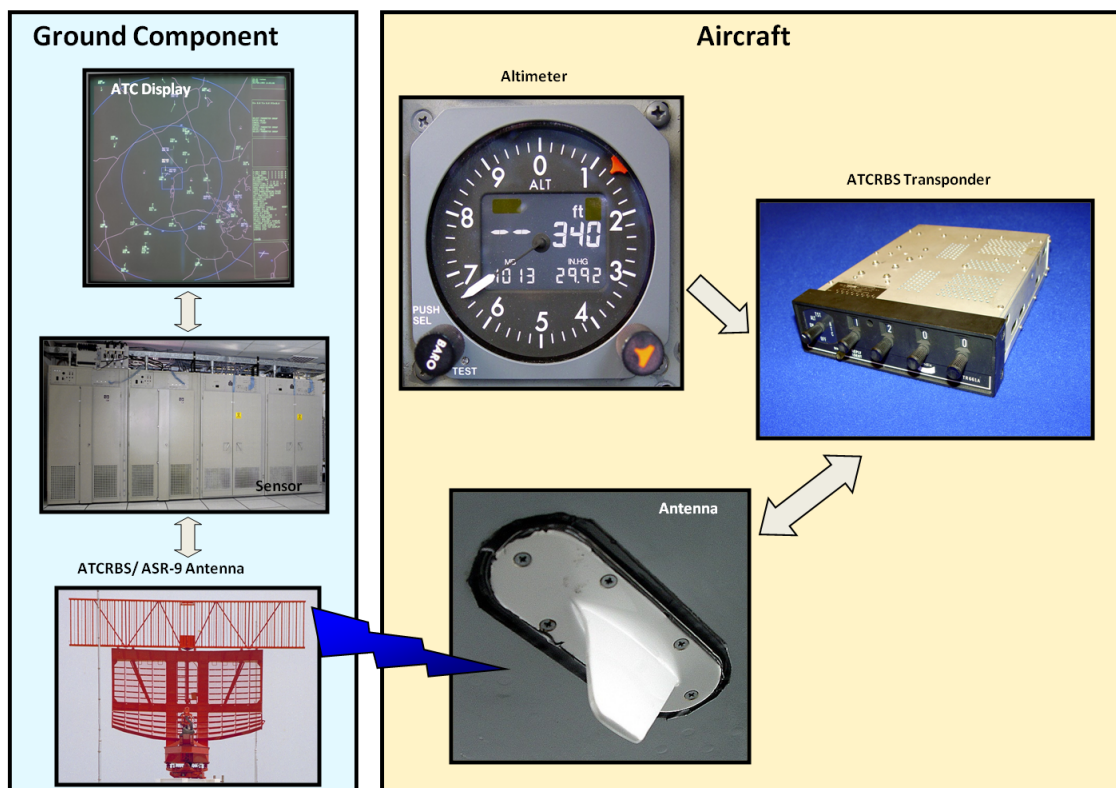


Figure 2.1. ATCRBS Communication Path. Ground hardware (left) and aircraft hardware (right) [2].

Figure 2.1 demonstrates the communication path used in secondary surveillance. Depicted are the following hardware items:

1. Ground Hardware

- The output of the Surveillance Data Processor (SDP) drives the ATC display (top);
- Ground-based transmitters and processors (middle); and
- An ASR-9 antenna topped by a Mode S antenna (bottom).

2. Aircraft Hardware

- Aircraft altimeter (top) communicates altitude to the transponder for transmission to interrogators;
- Panel mounted transponder used on General Aviation (GA) aircraft (middle); and
- Antenna normally located on the belly of the aircraft (bottom).

Typical radar installations contain a co-located PSR and SSR, and data from both radars are processed to compute reinforced aircraft position estimates.

The first generation SSR used for ATC was the Air Traffic Control Radar Beacon System (ATCRBS). Developed during the 1950s, it uses coded interrogations to request the transponder to transmit either the Mode A code (twelve bit ATC-assigned ID) or Mode C code (pressure altitude). This capability was needed to accommodate increased traffic density and is still in use today, both in the US and internationally.

Continued increases in air traffic density revealed shortcomings in ATCRBS that led to development of Mode Select (Mode S) surveillance. Every Mode S transponder has a unique 24-bit address [3]. Ground-based SSRs and Mode S transponders can exchange information using the datalink feature of Mode S, which provides flexibility far beyond the ATCRBS Mode A/C capability. Mode S transponders contain 255 56-bit registers which can be loaded with data from various aircraft sensors.

Early SDPs used data from ATCRBS and Mode S transponders to estimate aircraft velocity, altitude rate, heading, etc., by observing differences in aircraft position and altitude during consecutive radar sweeps. One problem with this approach is that the accuracy of these estimates is limited by the slant range and azimuth accuracy of the radar returns, and by the tracker algorithms of the SDP. During the 1980s, new aircraft began to be equipped with Flight Management Systems (FMSs) that use sophisticated digital computers to assist pilots, allowing them to fly more fuel-efficient trajectories. These FMS equipped aircraft were able to provide much better data estimates than the SDP could calculate, which led to interest in transmitting this data to ATC using the Mode S datalink.

European nations became interested in using the Mode S datalink to obtain specific aircraft state information to better optimize traffic flow in their crowded airspace, and began to put in place a series of equipment mandates during the early 2000s. Since aircraft-reported data would, for the first time, become an integral part of ATC operations, there was concern that the data should be validated to ensure that the aircraft data sources were reporting correct, consistent information, and that the transponder was correctly transmitting the data to the SSR. This led to the concept of

an Aircraft Surveillance Validation (ASV) framework to comprehensively evaluate aircraft-reported state data.

Lincoln Laboratory approached the USAF Electronic Systems Center in 2005 with an ASV proposal, and after some discussion on execution details, work commenced in 2006.

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3. MODE S DATA DESCRIPTION

When a Mode S transponder-equipped aircraft enters within range of a Mode S SSR, the aircraft is enrolled by the SSR into its list of tracked aircraft. The SSR is then able to downlink data from the aircraft's transponder. Data in the transponder are organized into registers, or data groupings, each of which has a unique address. Register information encoded and sent from the aircraft in a reply to an SSR interrogation is referred to as a "payload." The primary concern of validation is with the payload from registers 50_{16} (*five-zero*) and 60_{16} (*six-zero*), which contain physical state parameters. These two registers, along with 40_{16} , are the registers required to satisfy the European mandate for Enhanced Surveillance (EHS) [4]. Register 50_{16} contains the aircraft's ground speed, true track angle, track angle rate, and roll angle. Register 60_{16} contains the aircraft's barometric altitude rate, inertial vertical velocity, mach, and indicated airspeed. These items are described in detail in Section 7.

Validation of data items in registers 50_{16} and 60_{16} can be performed offline using recorded data from the SSR data stream. The stream includes the standard surveillance update payloads, including 50_{16} and 60_{16} , as well as basic radar surveillance data, discussed in Section 4.1. This data stream allows the reconstruction of the aircraft's physical parameters as well as access to the messages downlinked while the aircraft was enrolled with the SSR.

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4. DATA VALIDATION PROCESS

An independent estimate is calculated for each Downlinked Aircraft Parameter (DAP) using Basic Radar Surveillance Data (BRSD), discussed next. These data are used to validate a DAP (such as ground speed), discussed in Section 4.2.

4.1 Basic Radar Surveillance Data (BRSD)

BRSD is defined in this report as slant range, azimuth, and altitude. Slant range is the straight line distance of the aircraft from the SSR, shown in Figure 4.1. Azimuth is the aircraft's direction from the SSR as an angle in degrees clockwise from true North, shown in Figure 4.2. Altitude is the aircraft's pressure altitude above mean sea level. Slant range and azimuth are measured by the radar during communications with an aircraft and are encoded in the radar stream in addition to any payload data. Altitude is provided by the aircraft's altimeter via the transponder and is included in each reply to the SSR interrogation in addition to the register data requested. It is also published in the radar data stream.

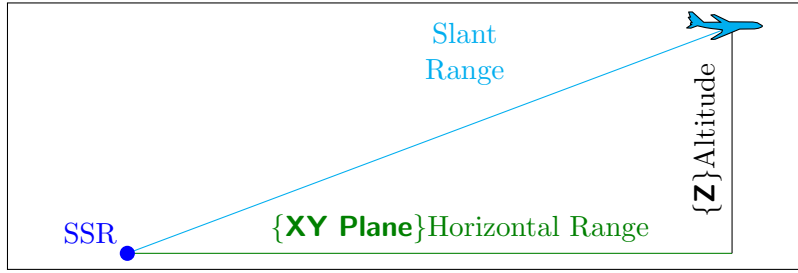


Figure 4.1. Ground range can be derived from slant range and altitude.
(Image does not consider curvature of the Earth)

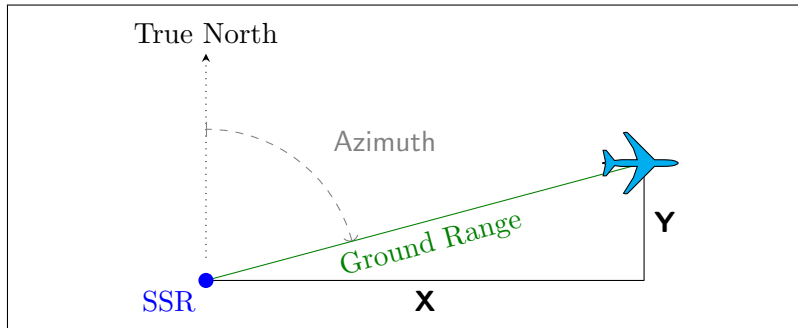


Figure 4.2. X (nautical miles East of SSR) and Y (nautical miles North of SSR) are calculated from ground range and azimuth.

The BRSD is regarded as “truth” data because the radar is calibrated by the Federal Aviation Administration (FAA), ensuring slant range and azimuth readings are reliable. Altitude is confirmed by pilot-controller dialogue each time an aircraft enters a new sector.

Using ground range, azimuth, altitude, and time, a four-dimensional path can be generated to form the basis for validating DAPs. Figure 4.3 depicts an actual path reconstructed using BRSD.

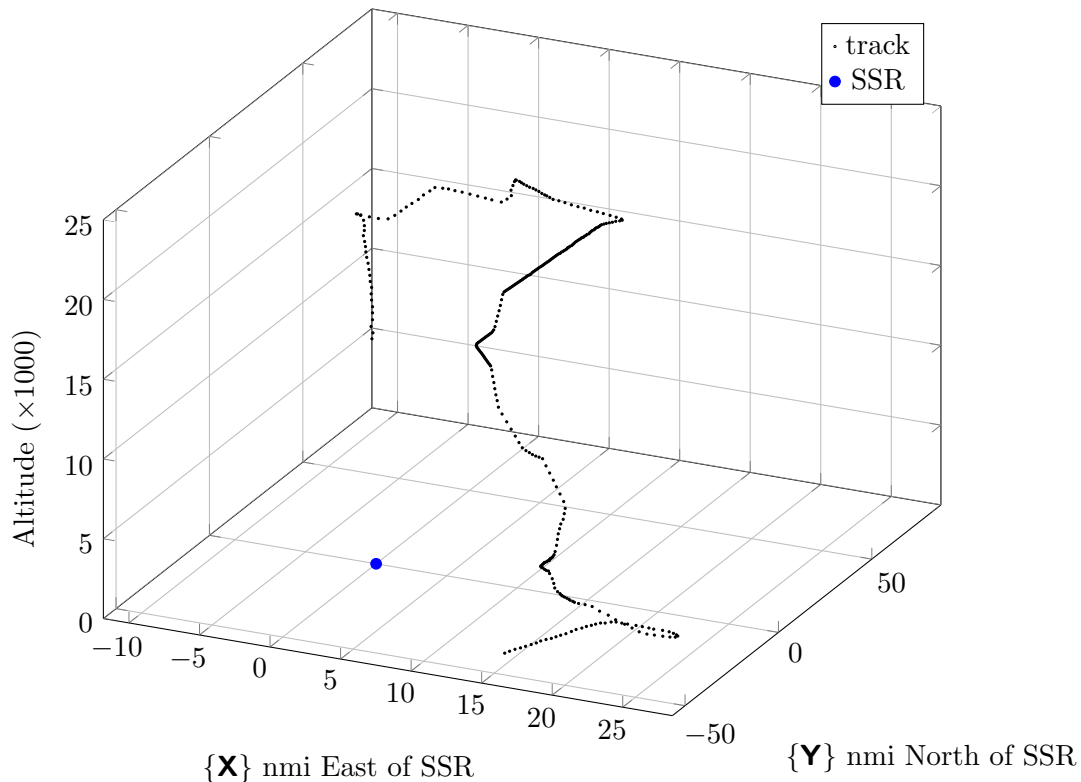


Figure 4.3. Track Segment

4.2 DATA ITEM VALIDATION TECHNIQUE

At the highest level, the technique used to validate DAPs can be described as utilizing the BRSD to calculate aircraft state data and comparing them to payload data. Testing that these two data sources remain consistent confirms that the payload data is reasonable, and the aircraft is reporting data as expected.

The path in Figure 4.3 represents BRSD updates, which are used to develop independent estimates for data items. To estimate ground speed, for example, horizontal position (i.e., X and Y location) and timing data can be used. Ground speed is the speed that the aircraft is traveling over the earth’s surface, so only horizontal position is required. The hypothetical aircraft in the sample

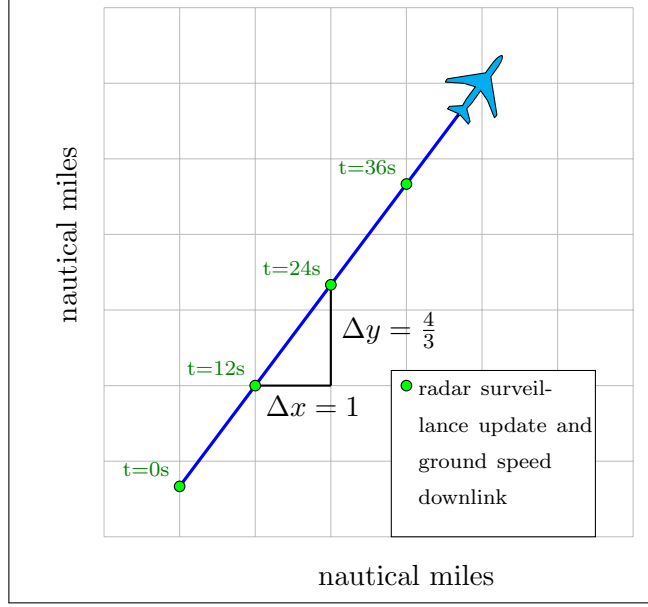


Figure 4.4. *Track in Horizontal Plane. Each dot represents a surveillance update (ground range, azimuth, and altitude) that has been projected onto the horizontal plane.*

track segment of Figure 4.4 has payload updates at 12 second intervals. BRSD measurements are always provided for the same times that payloads are retrieved. Assuming the first two payload downlinks include 50₁₆ payloads (ground speed data), the ground speeds at $t = 12$ s and $t = 24$ s can be validated by comparing the estimated ground speed calculated using the information from Figure 4.4:

$$\frac{\sqrt{\Delta X^2 + \Delta Y^2}}{\Delta t} \rightarrow \frac{\sqrt{(1)^2 + (4/3)^2}}{((24 - 12) \text{ s} \times \frac{1 \text{ min}}{60 \text{ s}} \times \frac{1 \text{ hr}}{60 \text{ min}})} = \frac{5/3}{0.0033} = \frac{5}{0.01} = 500 \text{ knots}$$

This result can be used to compare to, and *validate*, the downlinked ground speed payload at the 12 second and 24 second updates.

A similar process can be used to estimate true track angle, track angle rate, barometric altitude rate, and inertial vertical velocity. True airspeed, magnetic heading, and roll angle depend on ambient wind conditions in addition to BRSD data. In practice, BRSD is smoothed to increase the precision of the aircraft track. This allows better estimation of DAPs in the data validation process.

Since both smoothing and wind data are required for validating data items in registers 50₁₆ and 60₁₆, these are discussed in the next sections before continuing on to the details of each of the data items.

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5. SMOOTHING

Smoothing is applied to BRSD data in order to improve the accuracy of a reference track. Smoothing is never applied to DAPs that are being validated. All smoothing in the system is performed using a single smoothing technique often referred to as a point estimator. The process involves estimating the current point using surrounding points based on a 2nd order Taylor series expansion with respect to time.

Specifically, the system performs an adjustment of a measurement based on other measurements taken near the same time. A correlation between the set of points can be expected, and this expectation can be used in making the adjustment. For example, utilizing 7 total points to adjust the n^{th} measurement in a series of measurements using a second order Taylor series, the function looks like Equation (5.1), where \mathbf{A} has 7 rows, and \mathbf{b} has 7 columns. Each row in \mathbf{A} represents the estimate of the point b_n given an adjacent point b_m . The estimates from each row are used together to calculate a single adjusted value for b_n . Since Equation (5.1) is already generalized, changing the order of the smoother or the number of adjacent points used in the calculation only affects the composition of \mathbf{A} and \mathbf{b} .

$$\begin{aligned}
 \lambda_{(m)} &:= t_{b_m} - t_{b_n} \\
 \mathbf{b} &= \begin{bmatrix} b_{n-3} & b_{n-2} & \dots & b_{n+3} \end{bmatrix}^T \\
 \mathbf{A} &= \begin{bmatrix} 1 & b_n \lambda_{(-3)} & \frac{1}{2} b_n \lambda_{(-3)}^2 \\ \vdots & \vdots & \vdots \\ 1 & b_n \lambda_{(3)} & \frac{1}{2} b_n \lambda_{(3)}^2 \end{bmatrix} \\
 \hat{x} &= (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b}
 \end{aligned} \tag{5.1}$$

The procedure from Equation (5.1) takes any data vector \mathbf{b} and provides a smoothed value for each element by using the surrounding m points to the left and right of each b_n element. The first element of the vector solution \hat{x} is the adjusted value of b_n . However, this smoothing method is generalized and needs to be implemented for use in the system.

The system smooths track data as a two step process:

1. The azimuth measurements are smoothed because the azimuth measurement error can contribute more to the position error than slant range measurement (see Figure 5.1). The system currently uses seven total points to perform smoothing. Using smoothed azimuth, a local 3D position of the aircraft is calculated, with the SSR as the origin. Azimuth and ground range are referencing the SSR as the axes origin, but flight level is not. To account for this, information about the radar's height above mean sea level is used to compute height above the radar from altitude. The Data Dependency Chart in Figure A-2 depicts this.

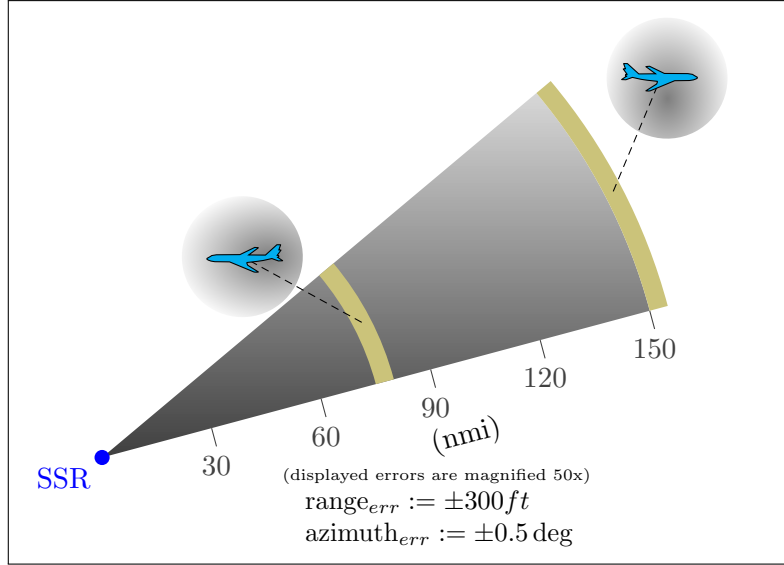


Figure 5.1. *Notional Azimuth vs. Slant Range Error. The azimuth error scales with slant range, whilst slant range error remains fixed. This compares slant range error and azimuth error at two different slant ranges. [5]*

2. The same technique used for azimuth is now applied to X, Y, and Z Cartesian data independently. This is done to remove jitter from the azimuth smoothed path. When smoothing the track, there is an expectation that the aircraft moves in a predictable manner. The result, for example, will take the actual track segment from Figure 5.2 and smooth what appear to be short severe back-and-forth turns into a more realistic aircraft track. Z is smoothed using five adjacent points, and X and Y have seven point smoothers.

Once the smoothing is complete, these data can be used in validation along with wind estimates, described next.

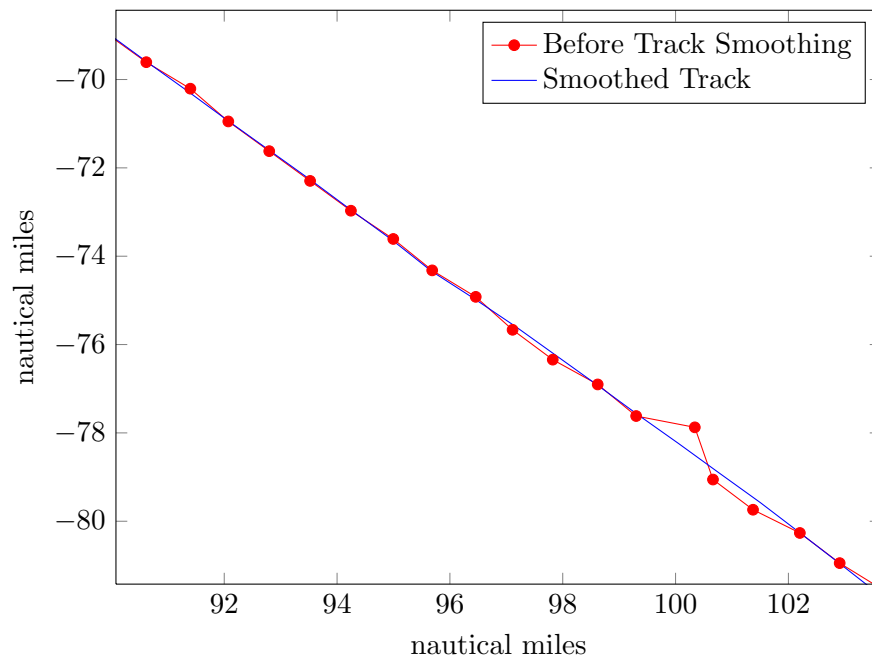


Figure 5.2. *Smoothing of Track Segment. The x and y axes represent nautical miles east and north of the SSR, respectively.*

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6. WIND VELOCITY ESTIMATION

Aircraft navigate between points on the earth's surface and must take into account the effect of wind on their flight path. In Figure 6.1, the pilot attempts to fly with a given ground speed and direction, \mathbf{G} . However, the wind, \mathbf{W} , is affecting the flight path and ground speed of the aircraft. In order to compensate, the pilot steers the aircraft to head in the direction of \mathbf{A} and adjusts the airspeed accordingly. If there were no wind, the pilot would maintain exactly the speed and direction he intends to travel. The wind triangle forms the basis for the wind estimation method.

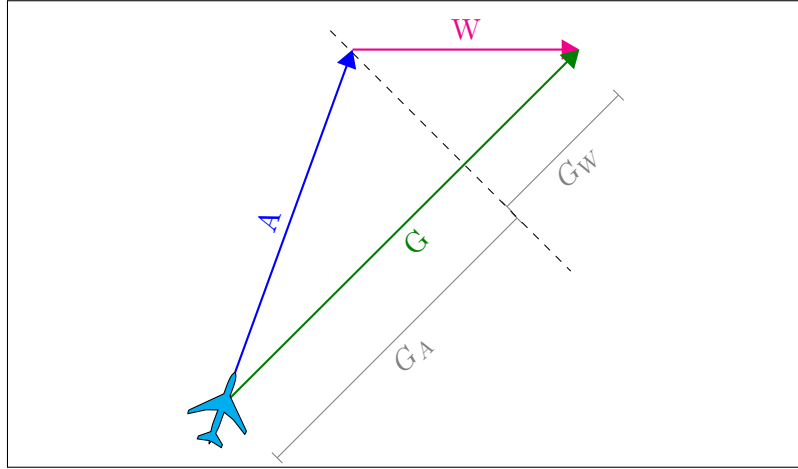


Figure 6.1. Wind Triangle Velocity Plot. \mathbf{A} is the aircraft's air velocity, \mathbf{G} is its ground velocity, and \mathbf{W} is wind.

The algorithms represent these speeds as vectors, which are indicated by bold text:

- \mathbf{W} = wind velocity
- \mathbf{G} = ground velocity
- \mathbf{A} = air velocity (velocity of aircraft through ambient air mass)

The ground velocity vector has two components: one for the ground velocity resulting from the airspeed (\mathbf{G}_A), and one for the velocity resulting from the wind (\mathbf{G}_W). The magnitude of the air velocity vector is the true airspeed, which is the actual speed of the aircraft through the ambient air mass. Figure 6.1 is a graphical representation of equation Equation (6.1)

$$\mathbf{G} = \mathbf{A} + \mathbf{W} \quad (6.1)$$

The speed due to wind and air velocity are the lengths of the vectors labeled G_W and G_A , respectively. The speed due to wind is calculated using

$$\|\mathbf{G}_W\| = \mathbf{W} \cdot \hat{\mathbf{G}} \quad (6.2)$$

and the total ground speed from wind and air velocity is:

$$\|\mathbf{G}\| = \mathbf{A} \cdot \hat{\mathbf{G}} + \mathbf{W} \cdot \hat{\mathbf{G}} \quad (6.3)$$

where $\hat{\mathbf{G}}$ is a unit vector in the direction of \mathbf{G} . Each velocity represented in Figure 6.1 has speed and direction components defined in Figure 6.2

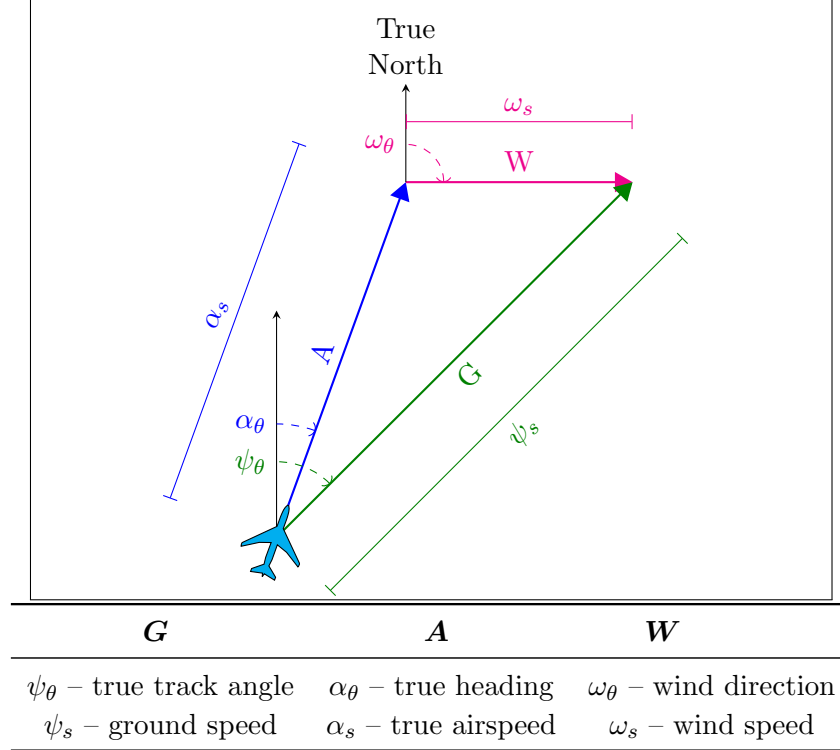
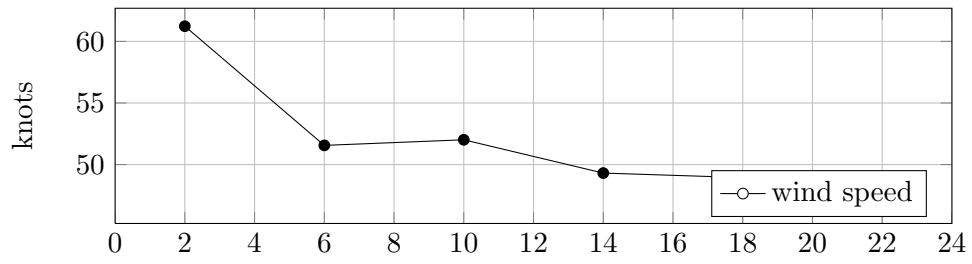


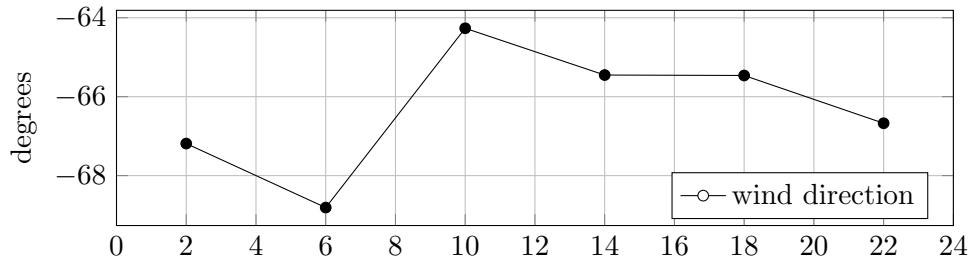
Figure 6.2. Wind Triangle Velocity Components

To solve for wind, the air and ground elements of Equation (6.1) are available from aircraft Mode S data.

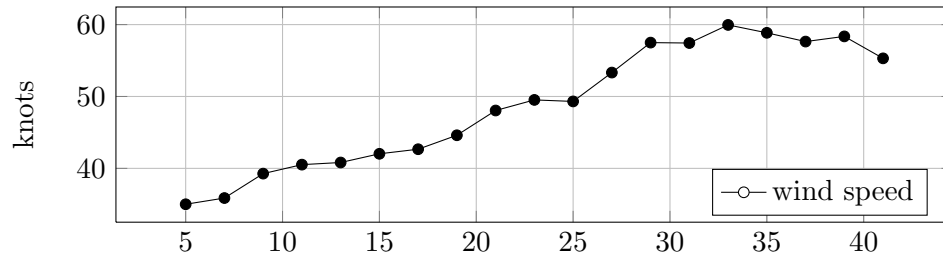
The parameters of \mathbf{G} are ground speed (ψ_s) and true track angle (ψ_θ), and \mathbf{A} is composed of true airspeed (α_s) and true heading (α_θ) as described in Figure 6.2. True heading is orientation of the aircraft in degrees clockwise from true North, whereas magnetic heading is referenced clockwise from magnetic North. This leaves the components of \mathbf{W} as the two unknowns in Equation (6.1): wind direction (ω_θ) and wind speed (ω_s). Two equations can be used to solve for the two unknowns. A single equation can be formed from each surveillance update that contains \mathbf{A} and \mathbf{G} data, which means a minimum of two updates are required to solve for wind. However, local variations in wind results in unrepresentative estimates when only two samples are used; Therefore, a more robust approach is warranted. Since there are usually many aircraft being tracked by a radar at any given time, there are abundant data available to include in the calculation. Performing a least squares



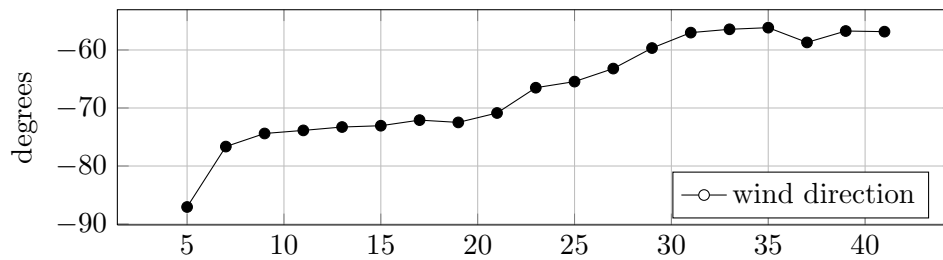
(a) Wind Speed by Hour of Day



(b) Wind Direction by Hour of Day



(c) Wind Speed by ft AMSL (x1000)



(d) Wind Direction by ft AMSL (x1000)

Figure 6.3. Change in Wind over Time and Altitude

analysis on a large sample set results in a more representative wind solution. For this calculation it is possible to make use of the data from all aircraft that the SSR surveils.

Using a large dataset to estimate wind also helps minimize the effect of erroneous data since any reported information from an aircraft has potential to contain errors. A large dataset is important in this respect because it allows all DAPs to be used as is (i.e., they do not need to be validated beforehand) for the purpose of estimating wind.

A linear equation relating air, wind, and ground velocities is used to perform the regression. One way of forming this is to write Equation (6.3) in its linear form, shown in Equation (6.5)

$$\begin{aligned}\|\mathbf{G}\| &= \mathbf{A} \cdot \hat{\mathbf{G}} + \mathbf{W} \cdot \hat{\mathbf{G}} \\ \psi_s &= \alpha_s \cos(\alpha_\theta - \psi_\theta) + \omega_s \cos(\omega_\theta - \psi_\theta)\end{aligned}\quad (6.4)$$

$$\underbrace{\omega_s \cos(\omega_\theta)}_{x_1} \cos(\psi_\theta) + \underbrace{\omega_s \sin(\omega_\theta)}_{x_2} \sin(\psi_\theta) = \psi_s - \alpha_s \cos(\alpha_\theta - \psi_\theta) \quad (6.5)$$

$$x_1 \cdot \cos(\psi_\theta) + x_2 \cdot \sin(\psi_\theta) = \psi_s - \alpha_s \cos(\alpha_\theta - \psi_\theta) \quad (6.6)$$

Equation (6.5) has the wind elements contained within coefficients of a linear equation. Equation (6.6) has substituted x_1 and x_2 for these portions of the equation. Using many samples, Equation (6.7) estimates x_1 and x_2 .

$$\begin{bmatrix} \cos(\psi_\theta [1]) & \sin(\psi_\theta [1]) \\ \vdots & \vdots \\ \cos(\psi_\theta [n]) & \sin(\psi_\theta [n]) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \psi_s [1] - \alpha_s [1] \cos(\alpha_\theta [1] - \psi_\theta [1]) \\ \vdots \\ \psi_s [n] - \alpha_s [n] \cos(\alpha_\theta [n] - \psi_\theta [n]) \end{bmatrix} \quad (6.7)$$

$$x_1 = \omega_s \cos(\omega_\theta) \quad (6.8)$$

$$x_2 = \omega_s \sin(\omega_\theta) \quad (6.9)$$

Equations (6.8) and (6.9) are then applied to solve for wind.

$$\omega_\theta = \arctan\left(\frac{x_2}{x_1}\right) \quad (6.10)$$

$$\omega_s = \frac{x_1}{\cos(\omega_\theta)} \quad (6.11)$$

The wind estimation method described above converges to a single wind speed and direction; this method must be applied to a localized region that can be described by the single result. The localized sample can then be used to generate a wind region estimate. The localizing regions are of four dimensions, bound by horizontal space (two dimensions), vertical space, and time. Variations in wind with respect to altitude and time exhibit significantly larger gradients than with respect to horizontal space. The system uses 2000-foot increments in altitude and time blocks of four hours. Horizontal space was not used to subdivide wind data because the extent of the radar was a small

enough area to be considered a single horizontal region. These region sizes were chosen based on gradients of the elements in the sample set used such that they produced usable results. Samples of wind gradients along the time and altitude dimensions are shown in Figure 6.3. The current region size is preliminary and was chosen as a reasonable starting point.

In opposition to reducing region size to an area with space-time invariant wind, is a need to increase region size in order to have a larger sample set to use in the calculation. Region size optimization is an area of further investigation.

The complete wind set over an entire radar coverage area for all time (where sufficient data exists), can be calculated using this process. Appendix B shows a sample of wind estimates for a given SSR over a one day period.

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7. DATA ITEM VALIDATION

The Data Dependency Chart in Figure A-2 gives an overview of the origin of the data used to derive estimates of the DAPs described in the sections below. A notated segment of that chart is shown in Figure 7.1. The requirements for compliance are published in [4]. These data are

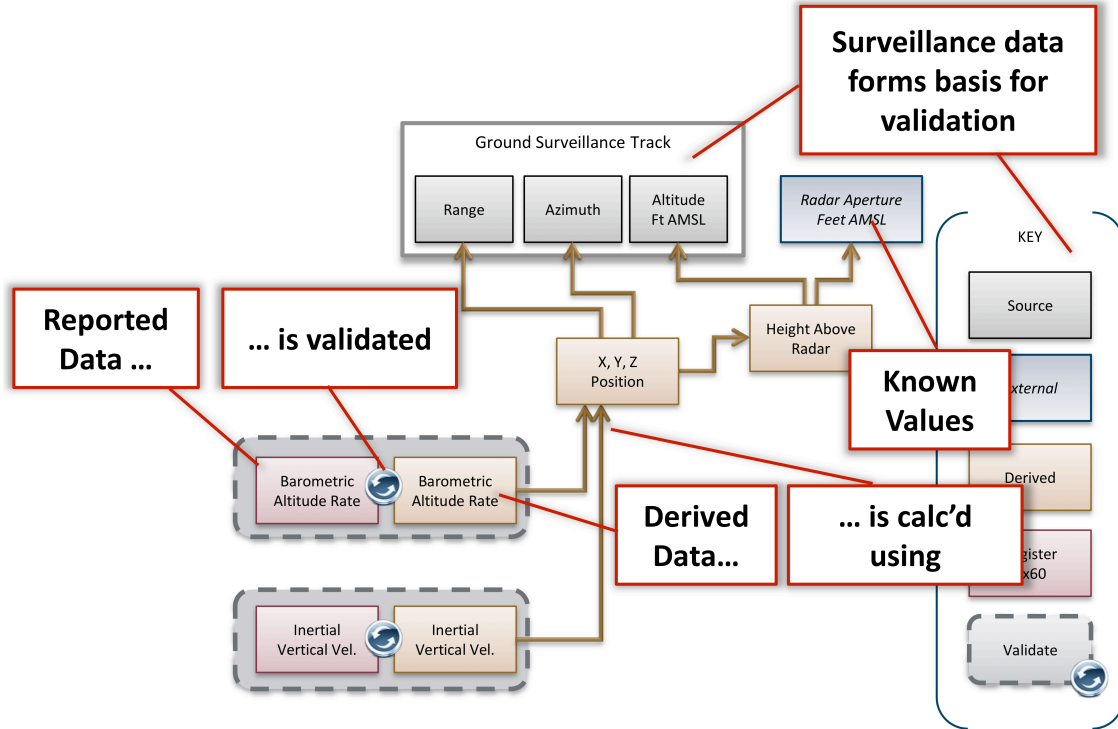


Figure 7.1. Data Dependency Chart Section

represented as “comprehensive surveillance data,” as shown in Figure 7.2. “External Data” include *a priori* knowledge about the radar’s location, and a model used for calculating magnetic declination, or the difference between true and magnetic north. Track Surveillance Data, or surveillance data, refers to BRSD. These include azimuth, slant range, and altitude. These items are considered to be always accurate. BRSD and wind data, collected over time, can be used to estimate ground speed, true track angle, track angle rate, barometric altitude rate, inertial vertical velocity, true airspeed, magnetic heading, and roll angle. A larger version of Figure 7.2 can be found in Appendix A. Before beginning any parameter estimates for a specific aircraft, described in the next sections, some basic data is prepared. These include calculations of aircraft position projected on a three-dimensional Cartesian coordinate system, and ambient wind. The aircraft position is the local X,Y, and Z position of the aircraft, calculated after smoothing the aircraft track. Wind information was described in Section 6. Position and wind vectors are prepared for each surveillance update in the track.

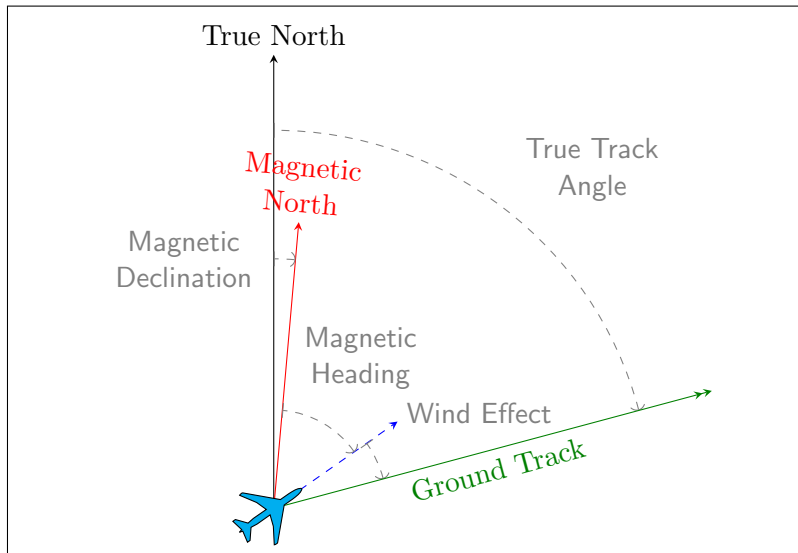


Figure 7.3. Wind, air, and ground velocity relationships from Equation (6.1). The G_A and G_W represent the air and wind contributions to ground speed, respectively.

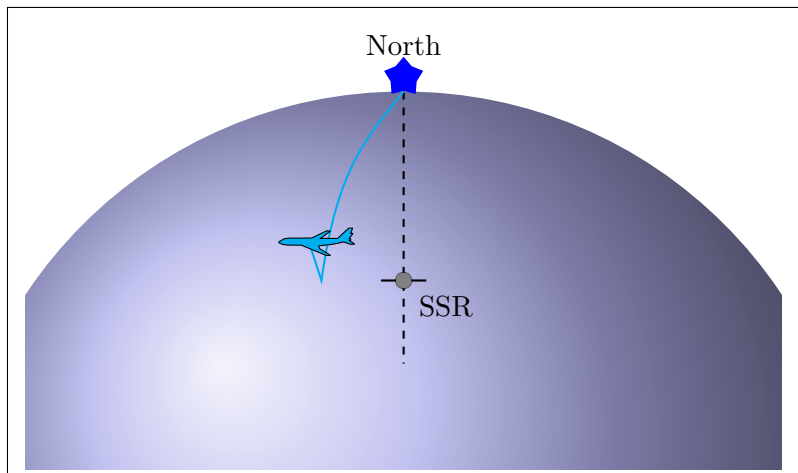


Figure 7.4. Each longitude has a unique true north direction. The system makes an assumption that true north is congruent for all locations within a radar's coverage area, which is not the case for significant longitudinal differences. Future versions are planned to account for this.

In combination with ground speed, true track angle forms the components of the ground velocity vector \mathbf{G} from Figure 6.2. True track angle is estimated by comparing the speed in the X direction with that in the Y direction at adjacent surveillance updates using Equation (7.2).

$$\text{atan2}(\Delta X, \Delta Y) + (LON_{SSR} - LON_{aircraft}) \quad (7.2)$$

The estimate of true track angle is based on BRSD and radar height source data, as specified in Figure 7.2 where atan2 is a quadrant resolving inverse tangent function, defined in piecewise form in Equation (7.3) [6]. Notice the argument order in Equation (7.2). This is because the atan2 function is based on the standard Cartesian plane with zero degrees along the positive x axis and angle increasing to the left. The system used for radar location uses zero along the positive y axis and angle increasing to the right.

$$\text{atan2}(y, x) = \begin{cases} \arctan\left(\frac{y}{x}\right) & x > 0, \\ \pi + \arctan\left(\frac{y}{x}\right) & y \geq 0, x < 0, \\ -\pi + \arctan\left(\frac{y}{x}\right) & y < 0, x < 0, \\ \frac{\pi}{2} & y > 0, x = 0, \\ -\frac{\pi}{2} & y < 0, x = 0, \\ \text{undefined} & y = 0, x = 0 \end{cases} \quad (7.3)$$

Note that the true track angle calculation is based on a Cartesian plane coordinate space with the origin at the SSR, and the Y axis extending towards true north. This forces the assumption that aircraft true north is parallel to the calculated SSR true north. As an aircraft increases its longitudinal distance from the SSR, the direction of true north deviates further from the Y direction. This effect is demonstrated in 7.4. The effect is larger closer to the earth's poles. By taking into account the longitudinal difference between the SSR and aircraft position, the true north direction at the aircraft position is found from the Y direction.

7.3 TRACK ANGLE RATE

Track angle rate is the horizontal turn rate of the aircraft. Track angle rate can be computed by examining the true track angle from Section 7.2 to determine how quickly it is changing with respect to time. The derivative of track angle with respect to time is shown in Equation (7.4).

$$\dot{\psi}_\theta = \frac{\Delta [\arctan(\frac{\Delta X}{\Delta Y})]}{\Delta t} \quad (7.4)$$

Consequently, shortening an aircraft turn radius while maintaining speed will increase the turn rate, as will increasing the speed while maintaining the same turn radius. In both cases the aircraft will be able to change heading more quickly. The estimate of track angle rate relies upon BRSD and radar height source data as specified in Figure 7.2.

7.4 BAROMETRIC ALTITUDE RATE

Barometric altitude rate is the change in the barometric altitude with respect to time. It can be estimated using the observed altitude from BRSD. The altitude measurement used for this calculation is converted from flight level and smoothed. This smoothed altitude data is different from Z for two important reasons. First, the Z plane extends vertically from the SSR aperture, whereas the altitude extends vertically at the location of the aircraft, which are not parallel due to the curvature of the earth (see Figure 7.5). Second, the Z direction always starts at the height of

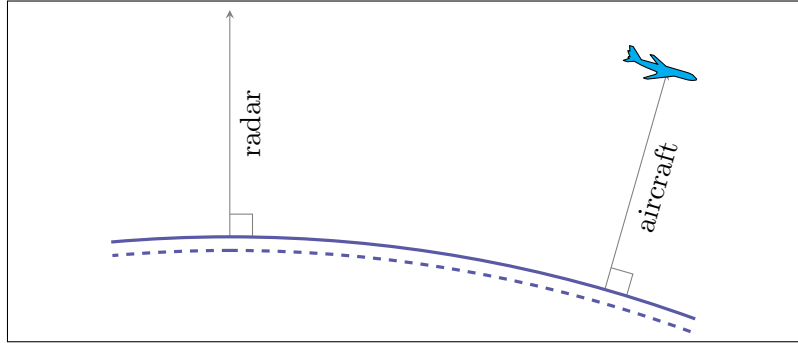


Figure 7.5. The curvature of the Earth results in a localized ‘vertical’ direction for every position above the Earth’s surface

the radar, and the smoothed altitude always starts at mean sea level. Since only flight level data is used to calculate the smoothed altitude, it is a less processed result and therefore is more accurate for the purpose of calculating barometric altitude rate. Equation (7.5) describes this.

$$\frac{\Delta Alt}{\Delta t} \tag{7.5}$$

7.5 INERTIAL VERTICAL VELOCITY

Inertial vertical velocity is the vertical movement of the aircraft. It is examined in the same way using the same reference data as barometric altitude rate.

7.6 TRUE AIRSPEED

True airspeed is the speed of the aircraft through the ambient air mass, or the magnitude of \mathbf{A} , $\|\mathbf{A}\|$. To calculate the air velocity, the wind estimation method and an aircraft’s reported ground velocity data are required. True airspeed is estimated by applying the aircraft’s reported ground velocity and the ambient wind, from the wind estimation method, to the wind triangle, Figure 6.1 on page 17. The magnitude of the air velocity is the true airspeed. The wind and

ground velocities in Equation (7.6) and Equation (7.7), from Equation (6.1) on page 17, are known.

$$\mathbf{G} = \mathbf{A} + \mathbf{W}$$

$$\mathbf{A} = \mathbf{G} - \mathbf{W} \tag{7.6}$$

$$\|\mathbf{A}\| = \|\mathbf{G} - \mathbf{W}\| \tag{7.7}$$

In practice, wind velocity is estimated using the wind estimation method from Section 6, and ground velocity \mathbf{G} is defined by the aircraft reported ground speed and true track angle, providing the magnitude and direction of the vector. Since the ground velocity data is collected from reported aircraft data it must be validated before it can be used to validate true airspeed. Therefore, if there is any question about the validity of either downlinked ground speed or true track angle, the air velocity estimate is also in question. This is handled by validating both ground speed and true track angle before using them to calculate air velocity. If there are any questionable results from either data item, a notation is made to the results of the data item validation sections that rely upon the air velocity calculation. The true airspeed and magnetic heading (discussed in Section 7.7) DAPs rely on the air velocity and therefore present this warning when appropriate. This is an acceptable implementation because the purpose is to find aircraft with potential issues. If there is an issue with ground speed or true track angle, this aircraft will already be identified in the Aircraft Specific Validation Report (ASVR).

7.7 MAGNETIC HEADING

Magnetic heading is the heading of the aircraft with respect to an onboard compass. The magnetic heading estimate is formed by rearranging Equation (6.1) and adjusting for magnetic declination, Equation (7.10). It is equivalent to the direction of the air velocity \mathbf{A} adjusted to magnetic north (air velocity has a direction from true north). This result is already available from the intermediate calculation for true airspeed validation, Equation (7.6), providing the data for Equation (7.9). The direction of the aircraft's air velocity is the true heading, or angle from true north that the aircraft is pointing. Magnetic Heading relies upon the assumption that aircraft true north is parallel to radar true north, discussed in Section 7.2. Converting the result, measured from true north, to a value based on magnetic north involves shifting the value by the local magnetic declination. The system uses a lookup table provided by National Geospatial-Intelligence Agency (NGA). This model is available at their website. [7]

$$M_H = \angle(\mathbf{G} - \mathbf{W}) - M_D \tag{7.8}$$

$$M_H = \angle(\mathbf{A}) - M_D \tag{7.9}$$

where M_H is magnetic heading and M_D is magnetic declination.

The implementation of Equation (7.9) used in the system is

$$M_H = \text{atan2}[\mathbf{G}_y - \mathbf{W}_y, \mathbf{G}_x - \mathbf{W}_x] - M_D \tag{7.10}$$

and $\text{atan2}()$ is defined by Equation (7.3) on page 26.

7.8 ROLL ANGLE

The amount of roll, or bank, of the aircraft can be estimated using a free body diagram with three forces: gravity, centripetal force, and lift. The aircraft roll allows lift to counteract the other forces and maintain level flight during a turn. Since horizontal velocities are much larger

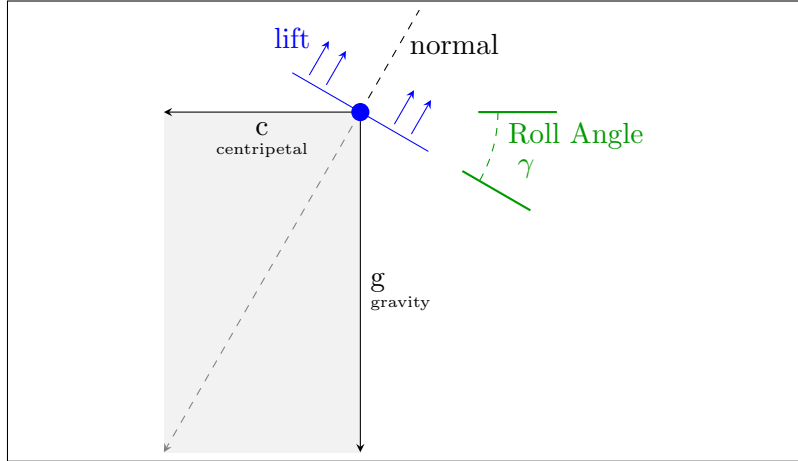


Figure 7.6. The roll angle of the aircraft is defined by the direction of the normal force. This simplified diagram shows the wings of an aircraft balancing both gravity and centrifugal force while turning.

than vertical velocities, vertical movement of the aircraft in the roll angle calculation is set to zero. The gravitational force is constant. Knowing the magnitude and direction (either left or right) of centripetal force is therefore sufficient to estimate roll angle. Equation (7.14) shows the calculation derived from the free body diagram in Figure 7.6. Roll angle to the right, or when the right wing is dipped, is positive roll angle. Centrifugal force is opposite centripetal force and can be expressed using angular momentum (ω) and radius of curvature (r) [8], and angular momentum can be expressed in terms of true heading rate, shown in Equation (7.12).

$$c = \omega^2 r \quad (7.11)$$

$$c = r \cdot (\dot{\alpha}_\theta)^2 \quad (7.12)$$

Roll angle can then be calculated using Equation (7.14).

$$\gamma = \arctan \left(\frac{c}{g} \right) \quad (7.13)$$

$$\gamma = \arctan \left(\frac{r \cdot (\dot{\alpha}_\theta)^2}{g} \right) \quad (7.14)$$

7.9 INDICATED AIRSPEED

Altitude ($\times 10^3$)	Normalized Air Density (ρ/ρ_{MSL})
0	1.0
5	0.8617
10	0.73859
15	0.62946
20	0.53317
25	0.44859
30	0.37473
35	0.31058
40	0.24708
50	0.15311
60	0.09492
100	0.01396

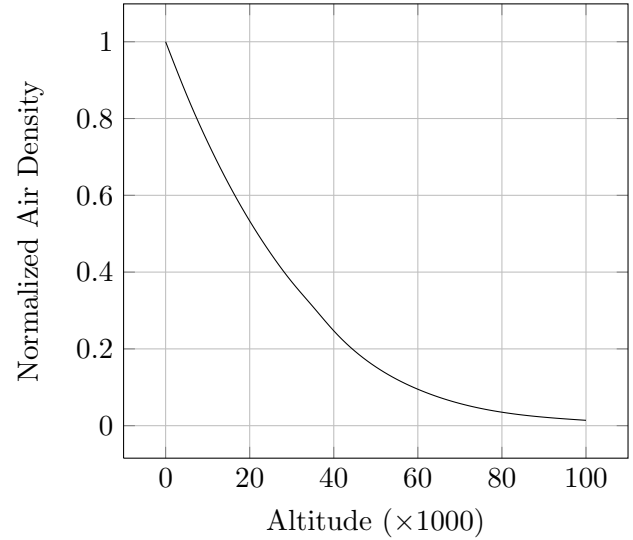


Figure 7.7. *Normalized Air Density. Sample points of relative air density (left) and a continuous interpolated air density function derived from those points (right). The sample points were taken from the table on p.334 of Schmidt’s Introduction to Flight Dynamics [9].*

Indicated airspeed is based on the instrumentation used in an aircraft. Specifically, it is a measure of the air pressure exerted on a sensor due to the velocity of the aircraft through the air mass. This measurement changes with the density of the air. At higher altitudes, the air density is less, so the pressure on the sensor due to equivalent true airspeed will also be less. Indicated airspeed will therefore decrease as altitude increases. As discussed previously, true airspeed is the actual speed of the aircraft through the ambient air mass. So if true airspeed and air density are known, it is possible to calculate the indicated airspeed using Equation (7.15) [9]. Since the system can estimate true airspeed, and air density can be estimated using altitude, it is possible for the system to provide validation for indicated airspeed.

$$IAS = \alpha_s \cdot \sqrt{(\rho/\rho_{MSL})} \quad (7.15)$$

Since the primary factor for air density is altitude, an approximation of indicated airspeed is the true airspeed adjusted for the expected air density given the altitude of the aircraft. Currently, the system uses a table lookup with a spline interpolator to estimate the air density at a given altitude. The air density is normalized to the air density at mean sea level. The base table, shown in Figure 7.7, contains a minimal number of altitude-density pairs. To find the density of an altitude that is not in the table lookup, a spline interpolation is used to generate a continuous function, which can be queried for any altitude. The function is valid for any value within or equaling the

minimum and maximum altitude samples in the base table, which are currently 0 and 100,000 feet above mean sea level (AMSL), respectively.

7.10 OTHER DATA ITEMS

Mach is also downlinked but is not validated. This is an area in need of further development.

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8. REPORTING

The current system, often processing thousands of aircraft tracks per day, is not one that can be reviewed using manual processes. It is necessary to compile the results of these tests and highlight the interesting data through use of automation and reporting. The reporting techniques rely on displaying and interpreting the calculated, downlinked, and error statistics of the various DAPs. The Aircraft Specific Validation Reports (ASVRs) and Cross Track Reports (XTRs) are based upon these data.

8.1 AIRCRAFT SPECIFIC VALIDATION REPORT (ASVR)

An ASVR provides data on a single aircraft track. It depicts the reported, estimated, and error values for each of the DAPs in 50_{16} and 60_{16} . An example of ground speed data is given in Figure 8.1. All parameters are enumerated in Figure A-2.

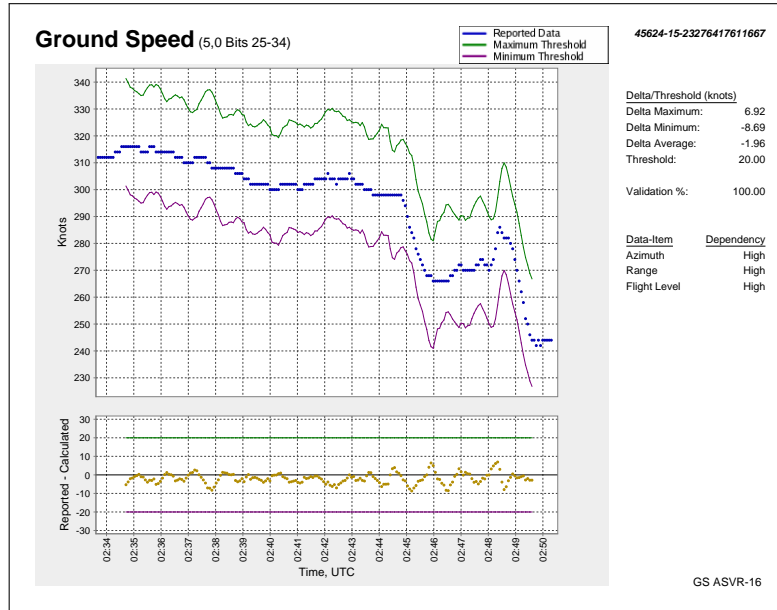


Figure 8.1. ASVR – Ground Speed. The reported values are represented in a time plot (top) using blue dots. The estimated parameters plus and minus the ground speed threshold are drawn as the two lines. The errors, or difference between reported and estimated parameters, are displayed in the bottom time plot. The green and magenta threshold lines are visible in both plots.

To create a plot of a DAP in the ASVR, its error and validation scores must be calculated. Error is the signed difference between the estimated and downlinked parameter values. If a down-

linked value has an error magnitude greater than a predetermined threshold, it is considered ‘not validated’ (i.e., it cannot be determined to be valid). Data items in agreement with the estimated value (within the threshold) are considered ‘valid.’ The thresholds are listed in Table 1.

TABLE 1

DAP Thresholds are based on engineering judgment. They are intended to discover any values that might be incorrect while ignoring errors which are commonly introduced during the track reproduction process.

Parameter	Threshold
Magnetic Heading	5 Degrees
True Track Angle	4 Degrees
Ground Speed	20 Knots
True Airspeed	20 Knots
Roll Angle	5 Degrees
Track Angle Rate	1 Degrees per Second
Inertial Vertical Velocity	200 Feet per Second
Barometric Altitude Rate	200 Feet per Second

Each DAP is tested and an overall validation percentage is calculated for the DAP over the entire track. If roll angle, for example, was downlinked 50 times, and 5 of those were values greater than one threshold away from the estimated value, the roll angle parameter for that track would be given a validation ratio of 0.9, or 90%. The term valid is interpreted as being close enough to the estimated value that the aircraft is likely reporting the data item correctly. However, ‘not validated’ should be interpreted that the data item does not fall within the threshold — the system on its own cannot determine if the data is inaccurate. As the validation ratio gets lower, it is more likely that a problem exists. It is up to the reader of the ASVR to further study the cause of the data being declared ‘not validated’ to determine if a problem exists.

Because an ASVR is generated for each qualified aircraft track in a dataset, there is a large number of ASVRs that need to be reviewed. To qualify, the track must contain at least 100 downlinks of EHS data. To handle the large number of ASVRs, a Validation Score (VS) is assigned to each ASVR based on its content. The VSs form a conceptual super-report, or a report of ASVRs. This scoring report lists the most interesting ASVRs first. Consequently, aircraft that contain mostly validated data across all of their DAPs will be listed towards the bottom. The VS is a relative scoring system, where a higher score indicates that the ASVR is ‘more interesting’. It is achieved by assigning a number of points based on the ratio of validated data and then scaling the points based on a DAP specific weight using Equation (8.1).

$$\text{Validation Score} = \sum_{\text{DAP}} \text{weight} \times \text{pts} \quad (8.1)$$

The point assignment is done through a binning system, where a validation ratio fits into a point range. For example, any validation ratio above 0.8 receives 0 (zero) points because it is within normal tolerance. The scoring values are listed in Table 2 and Table 3.

TABLE 2

Validation score weights

DAP	Weight
Magnetic Heading	1
True Track Angle	4
Ground Speed	4
True Airspeed	2
Roll Angle	1
Track Angle Rate	2
Inertial Vertical Velocity	2
Barometric Altitude Rate	2

TABLE 3

Validation score points

Validation Ratio	# of Points
> 80%	0
> 60%	2
> 50%	4
> 20%	6
Else	10

Each DAP has a weight. It is based on the interest level of the DAP and the confidence that a low validation ratio indicates a problem. For example, true track angle is of high interest and is validated with high confidence, therefore it is given a weight of 4, the largest weight in the calculation. The DAP weights are listed in Table 2. The weighted DAP scores are summed to provide a validation score for the ASVR as in Equation (8.1).

8.2 CROSS TRACK REPORT (XTR)

The validation score is one of two methods used to look for reporting problems. The second method is by filtering the aircraft with the largest relative errors in a dataset with many aircraft.

For a given set of data with many aircraft, an ASVR is generated for each aircraft, whereas a single Cross Track Report (XTR) is generated for the entire set. Furthermore, the ASVR assists in finding data items that are being reported incorrectly with high frequency, whereas the Cross Track Report (XTR) identifies large errors that occur, regardless of their frequency. For example, if a single track angle rate DAP value resulted in an error much larger than what other aircraft tracks seem to be exhibiting, it suggests that there may be some issue worth further investigation. The XTR is designed to provide a visual representation of the results. It shows both maximum absolute error in the DAP for a track and the average absolute error as a two-tiered bar in a bar chart. Figure 8.2 provides an example. An entire report sample is included as Appendix D. This report provides a way to find outliers, and can help direct the report reader to significant problems that can be investigated further by inspection of an ASVR. The reader can then use the ASVR filename in the right column as a hyperlink to open the report.

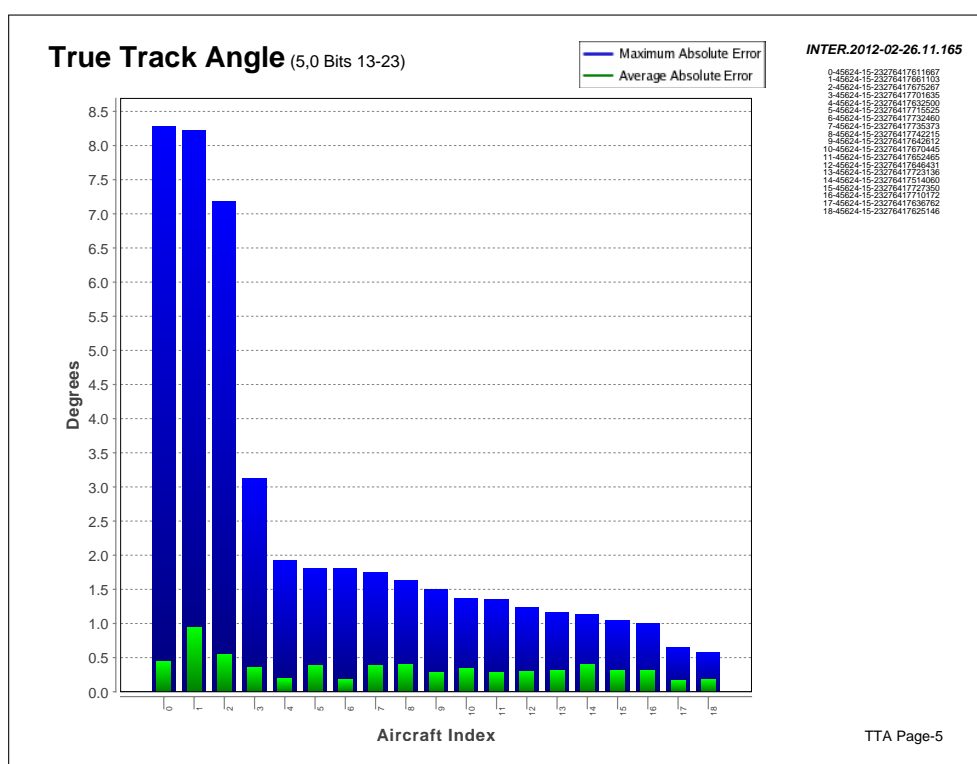


Figure 8.2. XTR – track angle rate plot. Two aircraft tracks seem to be exhibiting large track angle rate errors. The index to the right hyperlinks to the Aircraft Specific Validation Report (ASVR) associated with each of the given tracks represented by the error bars.

9. CONCLUSION

The current system analyzes aircraft tracks and identifies potential issues with DAPs. It stores the generated results and is capable of distributing, via email, summary data to user-defined recipients on a periodic basis. It is designed to recover, if possible, in the event of an error or external disruption which causes the system to fail. This system has been an invaluable resource for the discovery and identification of aircraft issues for the United States Air Force (USAF). It is being used as an ongoing monitor to find new potential problems, and has been used in the past as a resource to help analyze existing problems and answer specific questions about the surveillance process asked by the USAF and affiliates.

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10. FUTURE WORK

The system will continue to be modified to increase the reliability, accuracy, and precision of its algorithms in order to further reduce false-positive reporting and increase the confidence of its results. In addition, the system will be expanded to process and validate more DAPs elements, starting with the elements contained in register 40_{16} , and possibly the remainder of 60_{16} and expanding into registers defined in Automatic Dependent Surveillance – Broadcast (ADS-B) as part of the Next Generation Air Transportation System (NextGen) [10].

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APPENDIX A DATA DEPENDENCY CHART

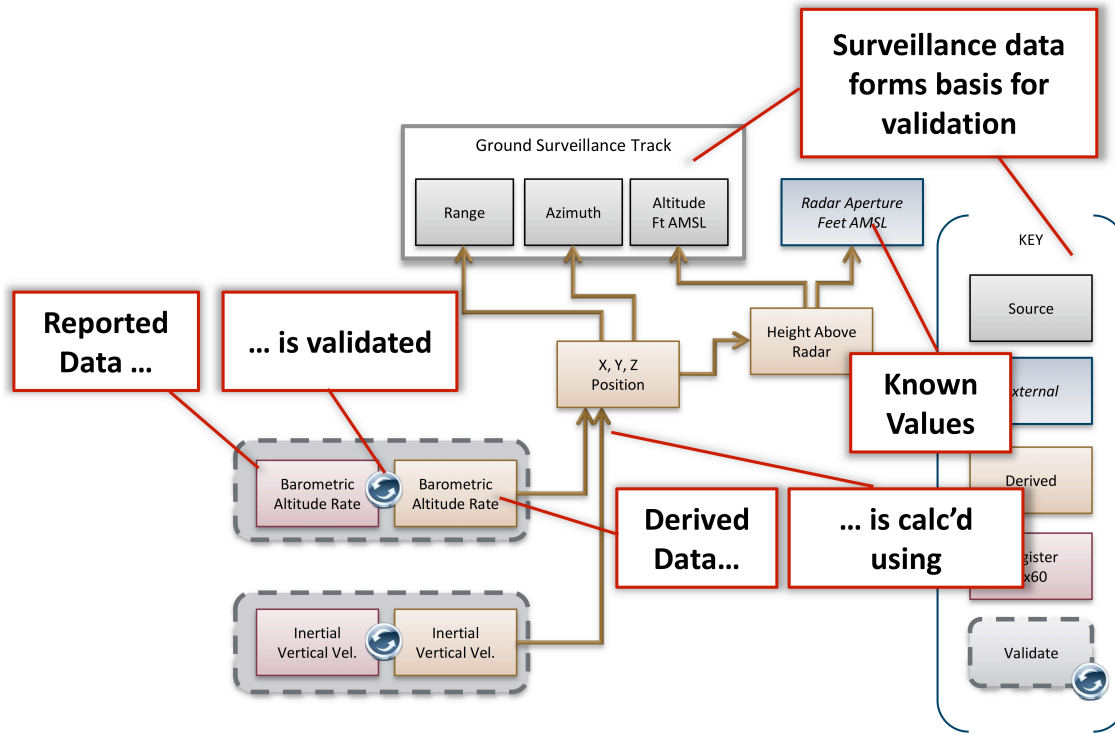


Figure A-1. The data dependency chart describes an hierarchy of data dependencies for calculating parameter estimates. Above, the barometric altitude rate depends on Position, which in turn is calculated using other data items.

Figure A-1 describes how to interpret the Data Dependency Chart in Figure A-2. In Figure A-1 the *Ground Surveillance Track* refers to the Basic Radar Surveillance Data (BRSD) data that is considered reliable. The chart depicts that *height above radar* can be determined if both the aircraft's height above mean sea level (AMSL) and the radar's height AMSL are known. Specifically, it defines the dependencies of a given data item as in Equation (A-1), as well as others.

$$\text{height above radar} = f(\text{radar AMSL}, \text{aircraft AMSL}) \quad (\text{A-1})$$

$$\text{position} = f(\text{slant range}, \text{azimuth}, \text{height above radar}) \quad (\text{A-2})$$

$$\text{barometric altitude rate} = f(\text{position}) \quad (\text{A-3})$$

$$\text{inertial vertical velocity} = f(\text{position}) \quad (\text{A-4})$$

Finally, the reported data in Figure A-1 shows that the barometric altitude rate and inertial vertical velocity from 60₁₆ can be validated using these derived data.

In the complete chart shown in Figure A-2 there is also a section of source data labelled *comprehensive downlinked aircraft parameters*. This refers to data collected by the Secondary Surveillance Radar (SSR) regarding all aircraft. This data from all aircraft is used to estimate the wind characteristics. This should not be confused with the data in the *ground surveillance track* area. This information is only from a given aircraft, and is used to generate flight characteristics.

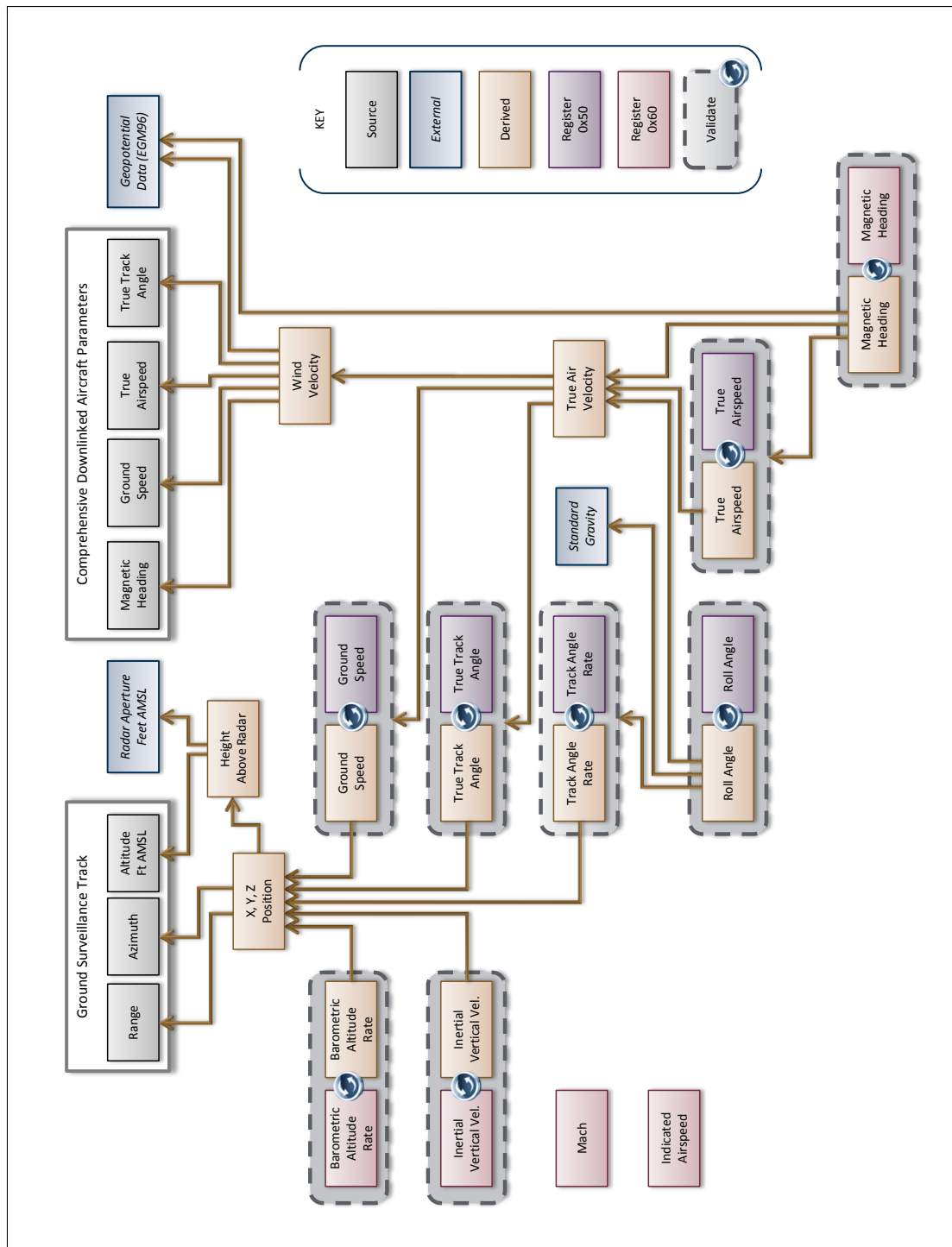


Figure A-2. Data Dependency Chart

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APPENDIX B WIND FIELD SAMPLE

The wind field report is a pdf report generated by the system. It always contains a single day of wind information. The wind report consists of a title page that identifies the report and a series of pages containing graphical wind data. It is organized by altitude and time as described in Figure B-1. The following pages of this appendix show a wind field that was generated by the system.

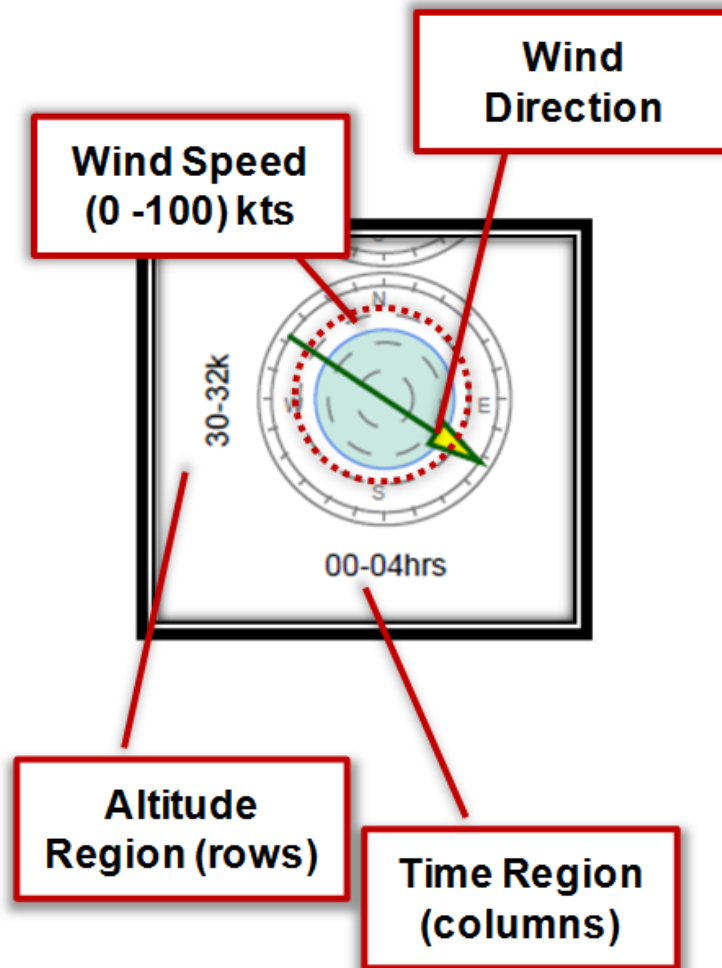


Figure B-1. Reading the Wind Field Diagram

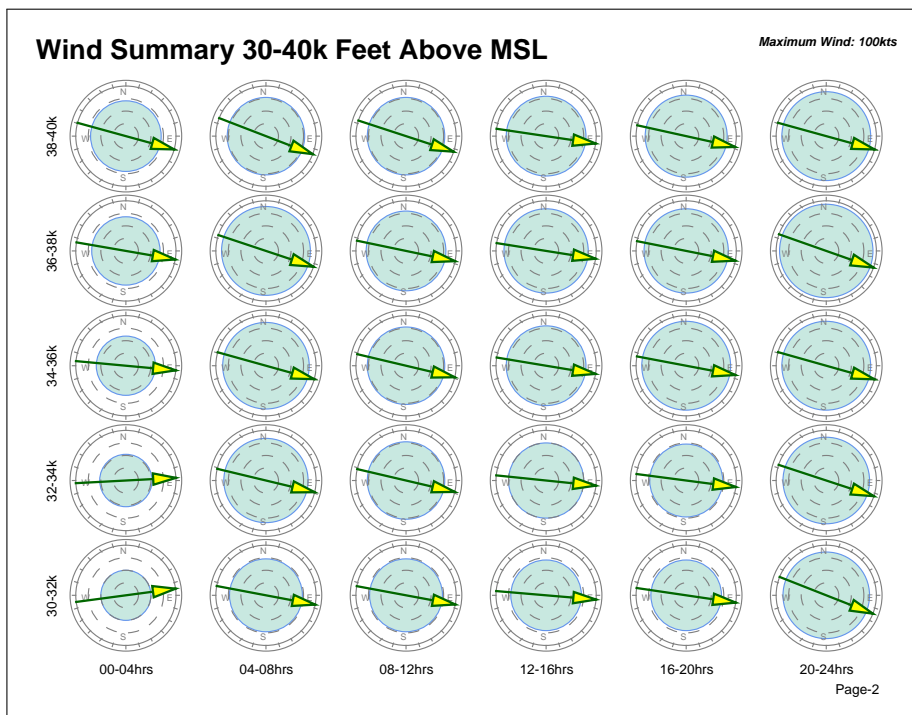
Wind Summary Report

Elwood: New Jersey, USA

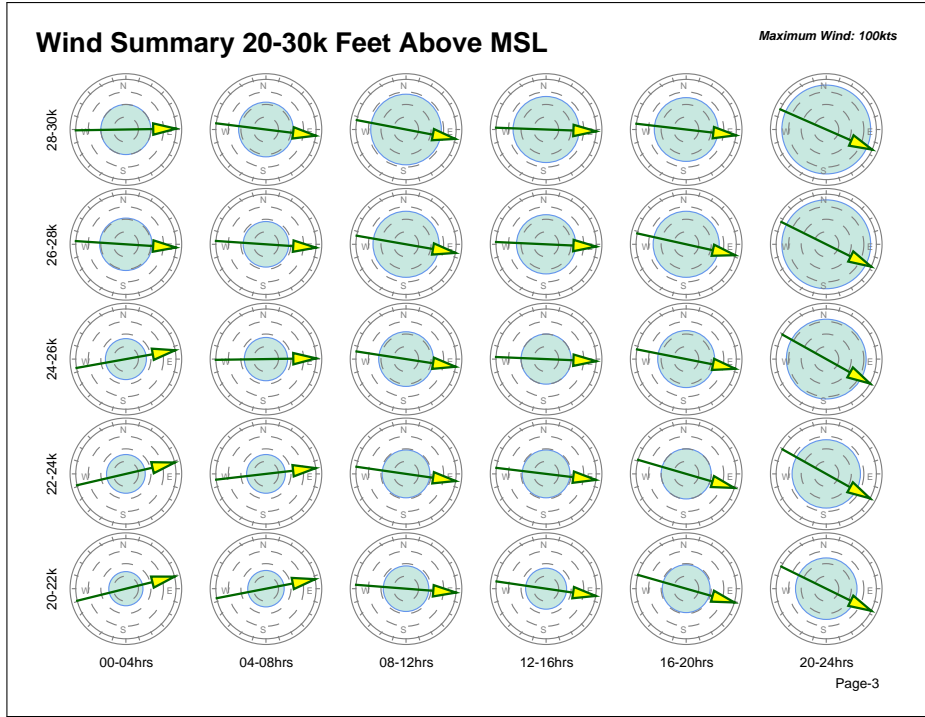
SAC: 193 - SIC: 0

2012-02-15

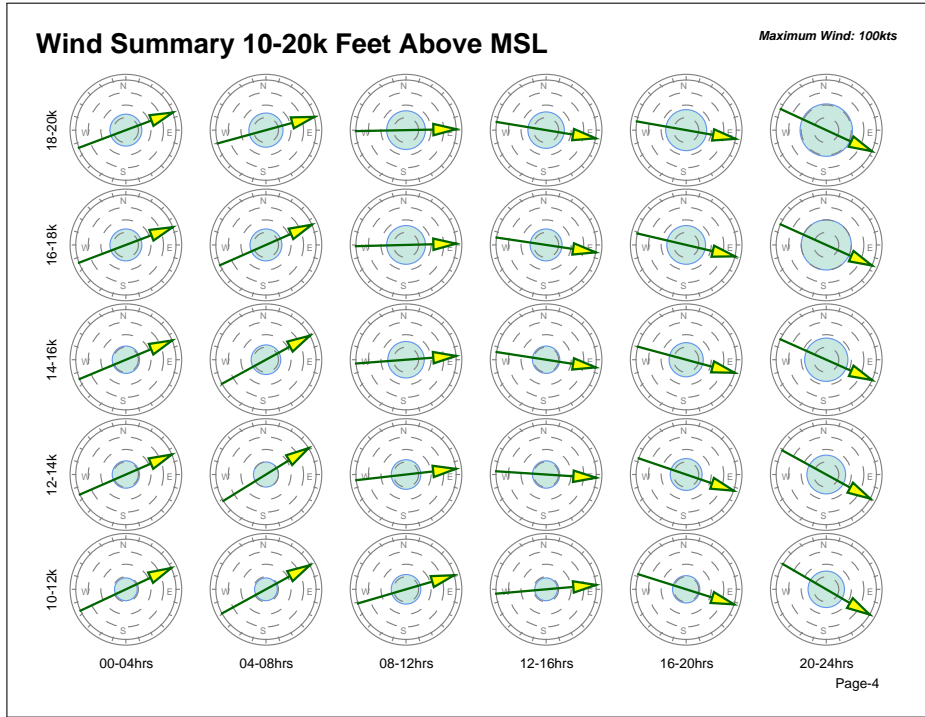
PDF Scan B.1: Wind Field Part 1 of 5



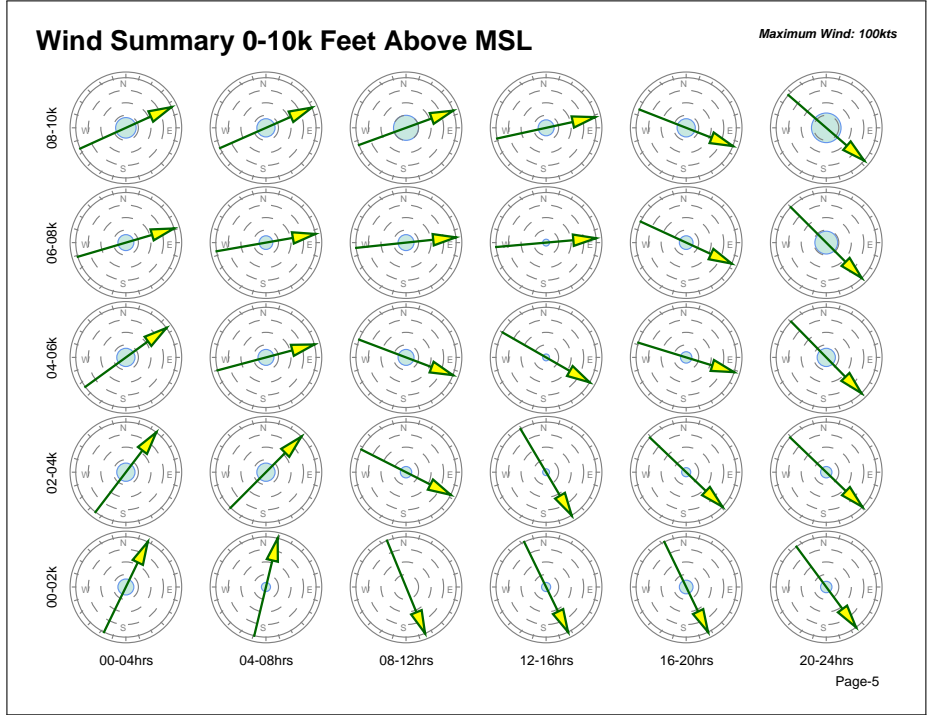
PDF Scan B.2: Wind Field Part 2 of 5



PDF Scan B.3: Wind Field Part 3 of 5



PDF Scan B.4: Wind Field Part 4 of 5



PDF Scan B.5: Wind Field Part 5 of 5

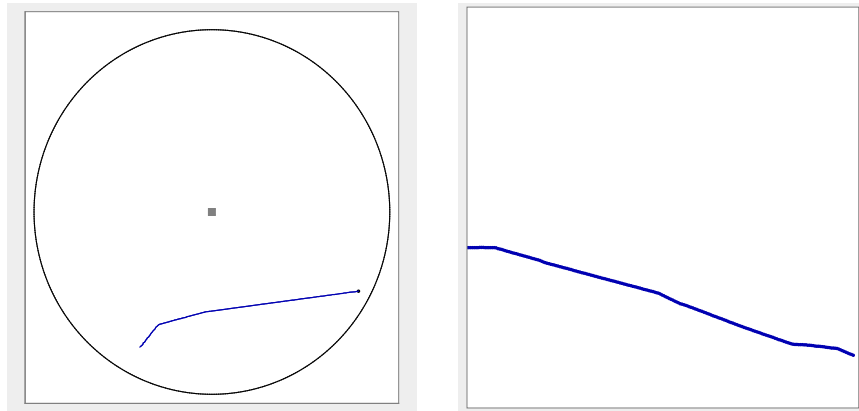
APPENDIX C

AIRCRAFT SPECIFIC VALIDATION REPORT (ASVR) SAMPLE

Aircraft Specific Validation Reports (ASVRs) are generated by the system. Each track that meets a contains a minimum amount of data, defined in the system setup, has an associated ASVR generated. This report provides view of the data that is easily accessible to the user.

Page 2 of the ASVR example, titled “Flight Summary,” has been redacted for anonymity purposes, but would normally contain identifying information and characteristics of the radar source and the aircraft.

Aircraft Specific Validation Report

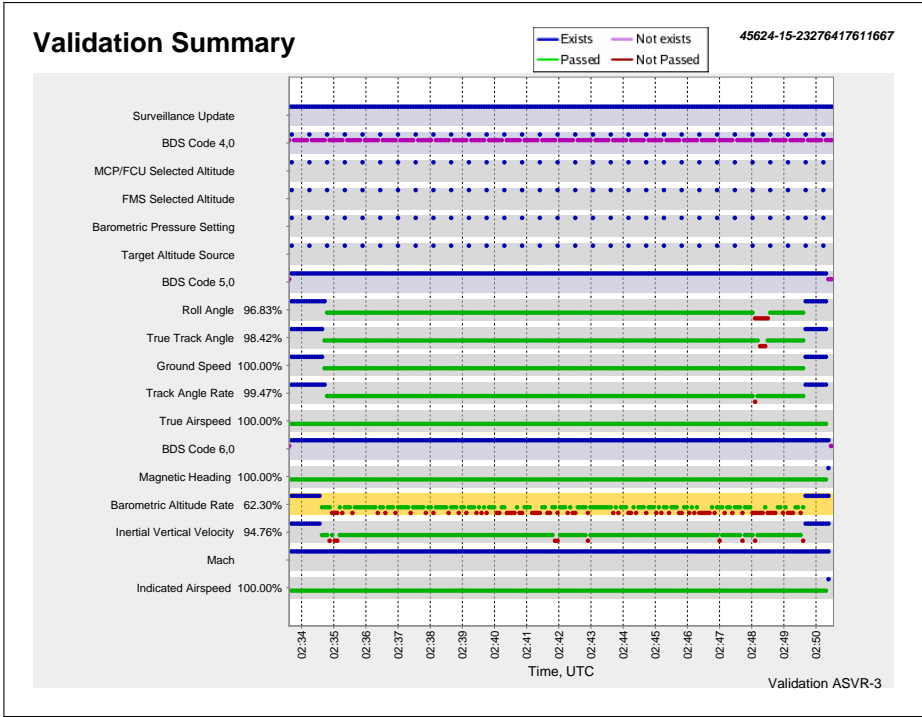


PDF Scan C.1: ASVR Page 1

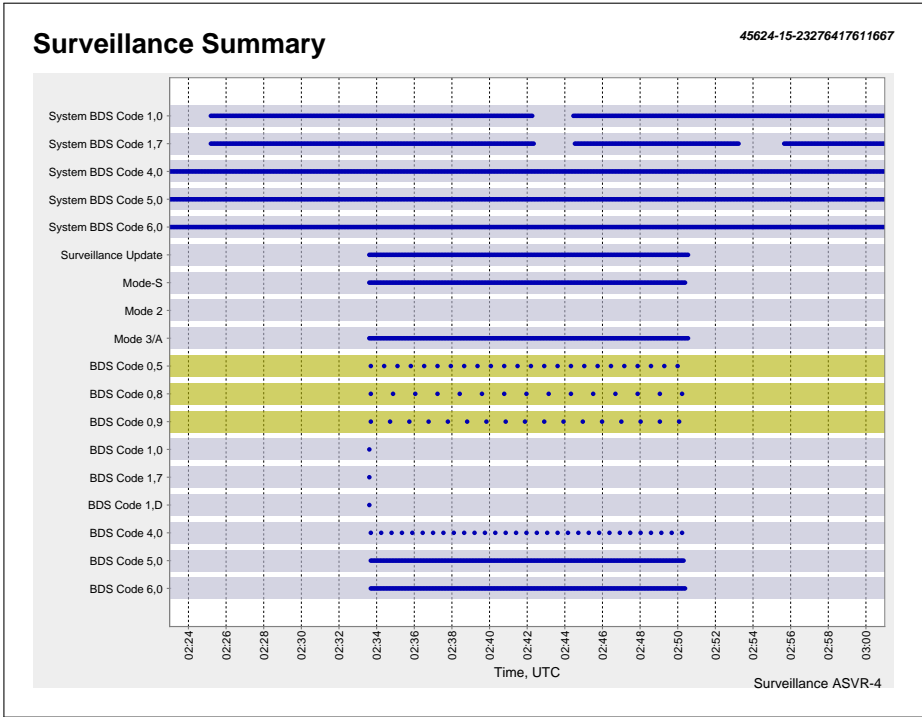
Flight Summary



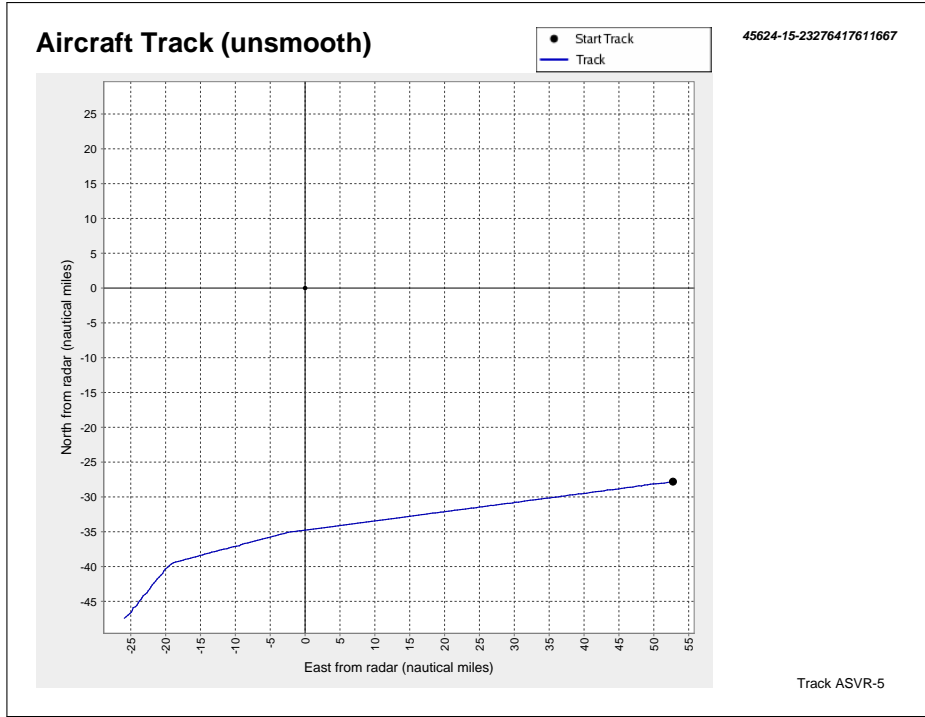
PDF Scan C.2: ASVR Page 2



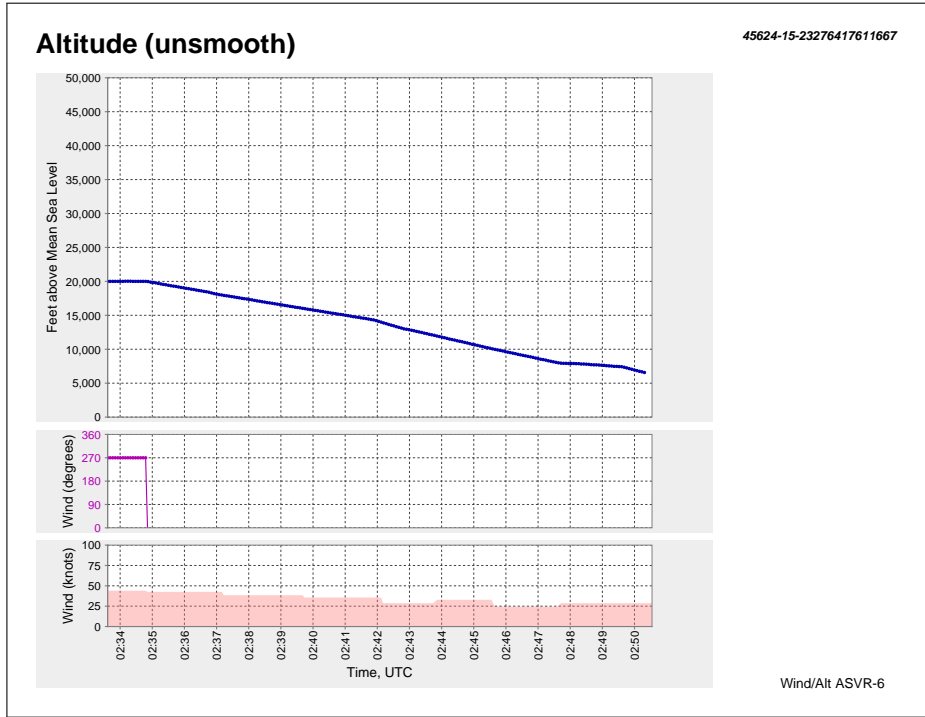
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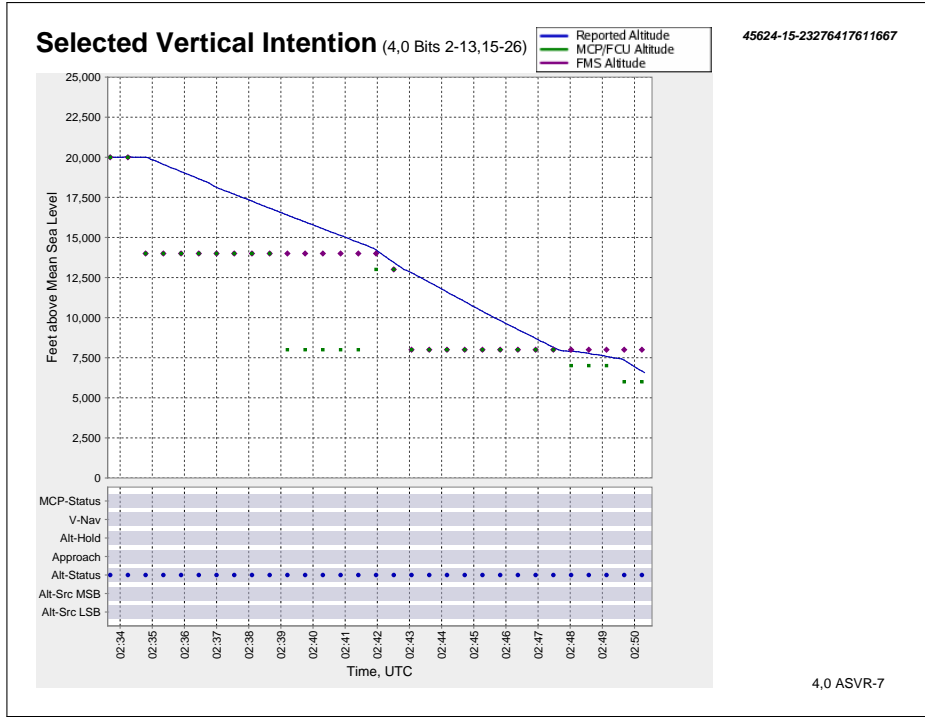
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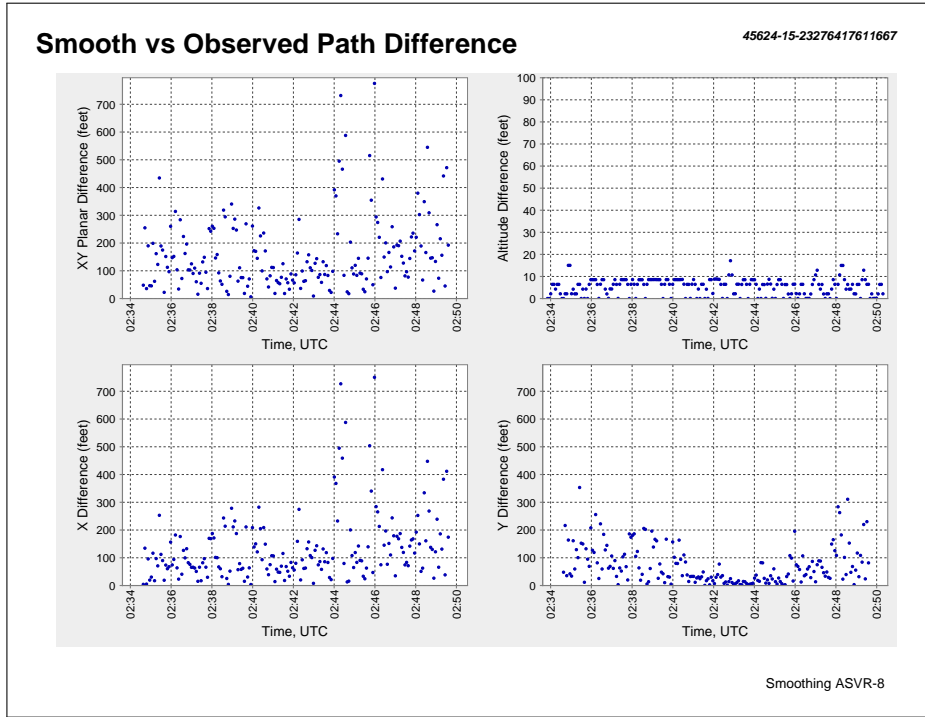
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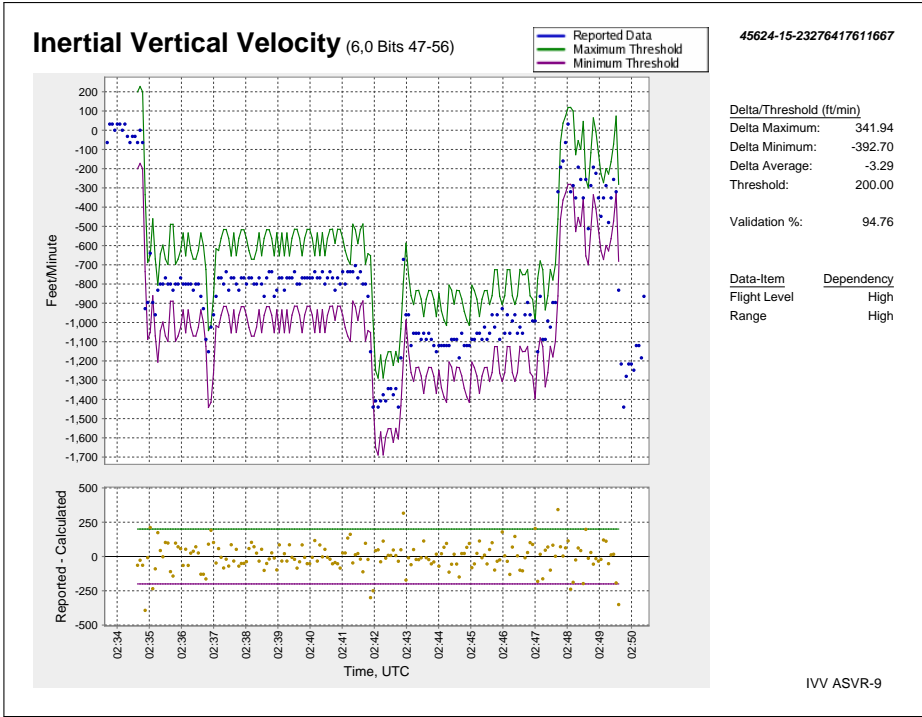
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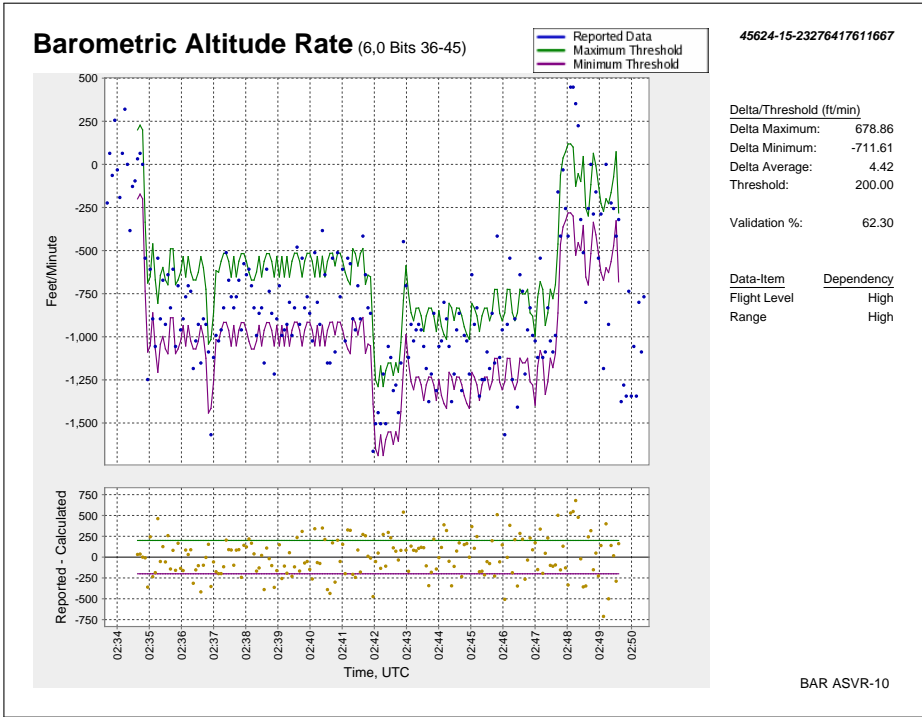
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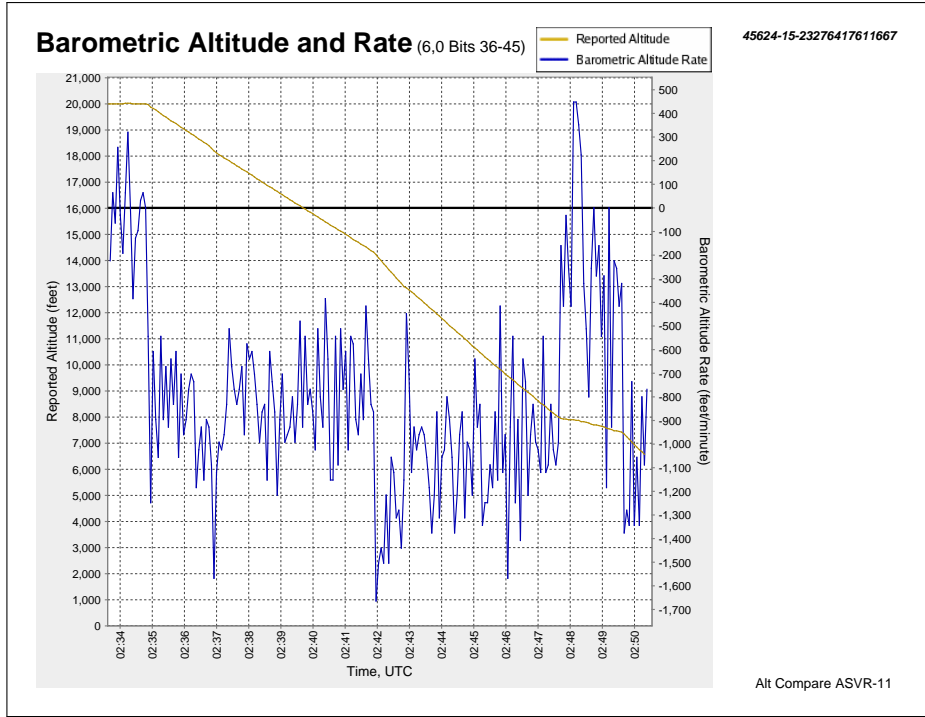
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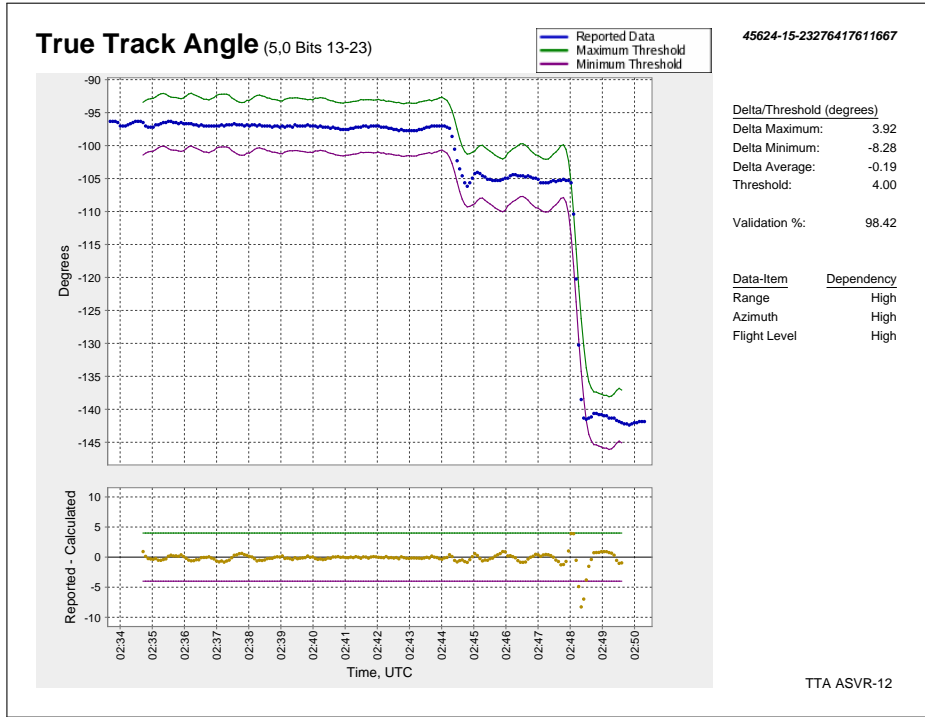
PDF Scan C.9: ASVR Page 9



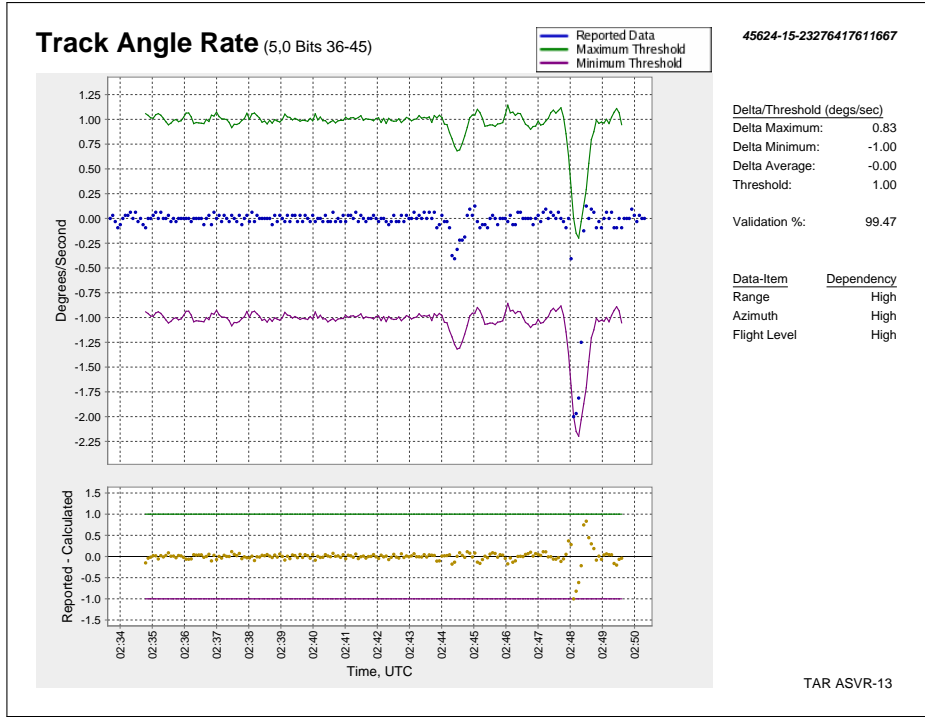
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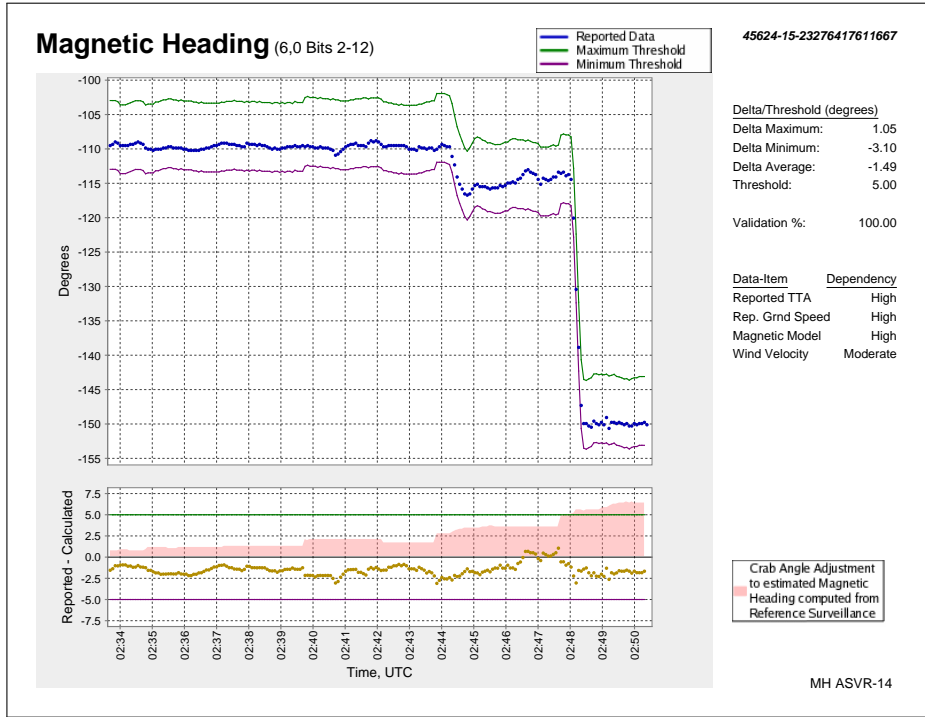
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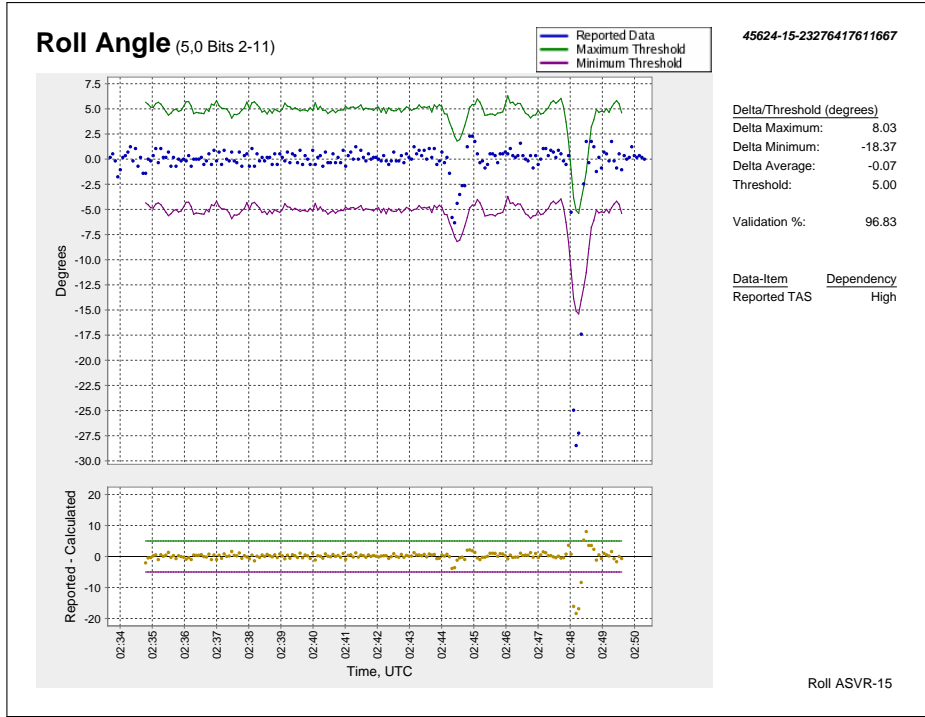
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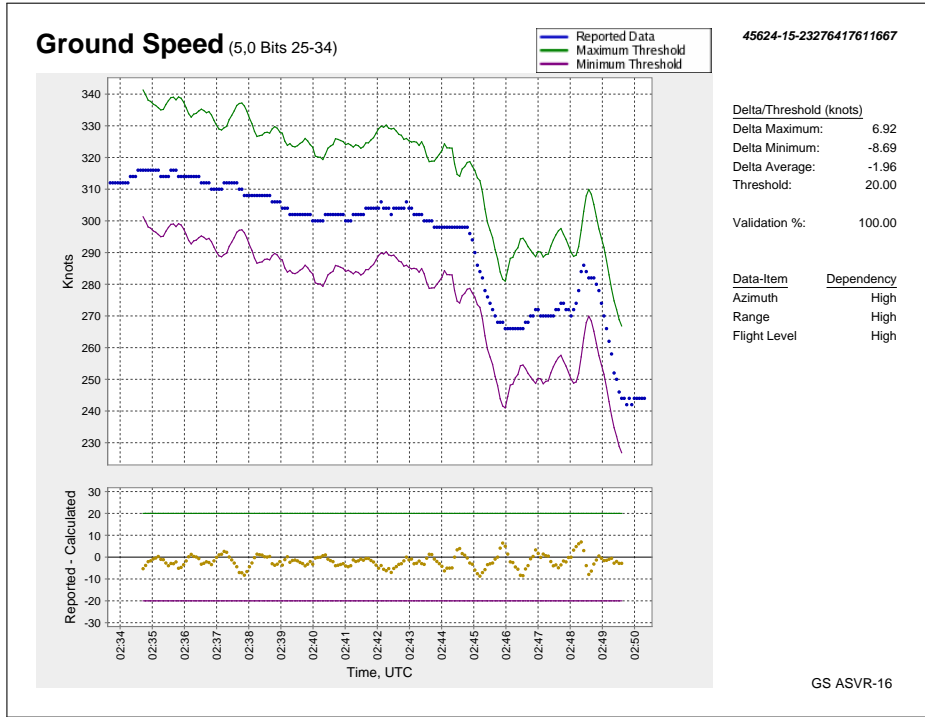
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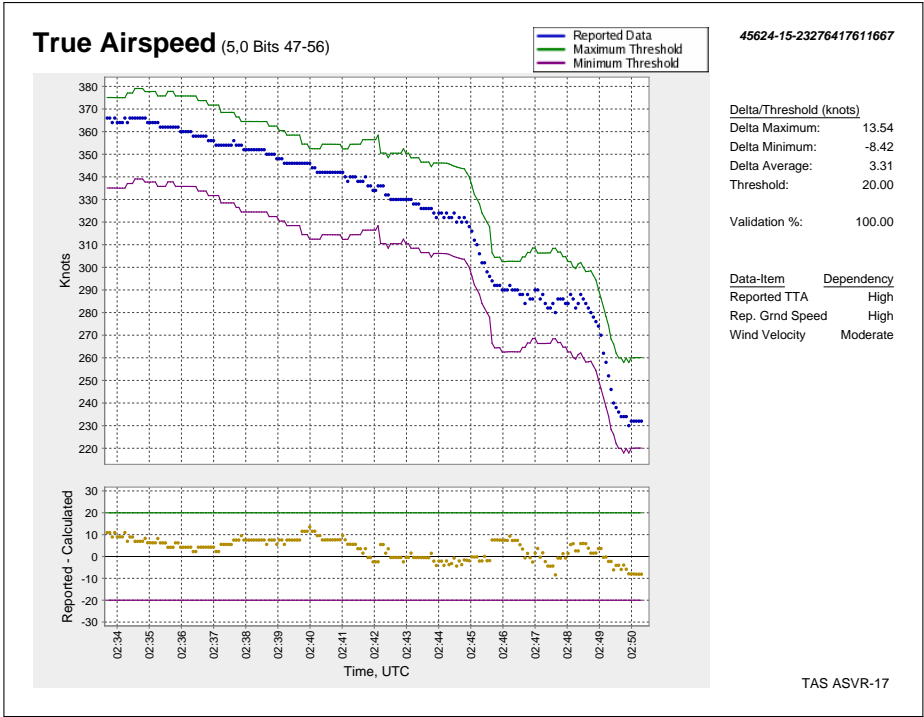
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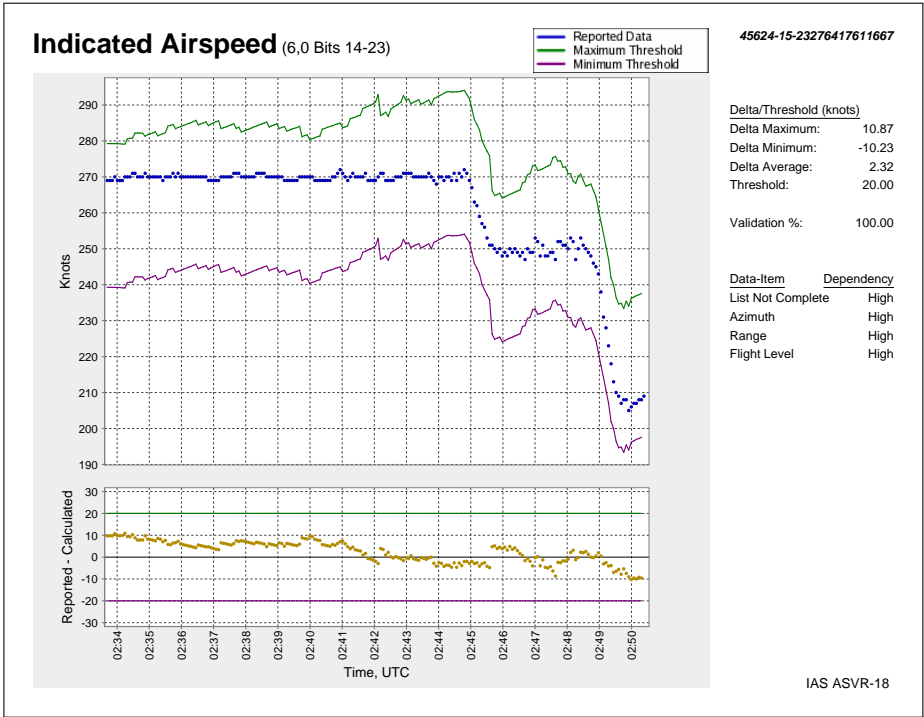
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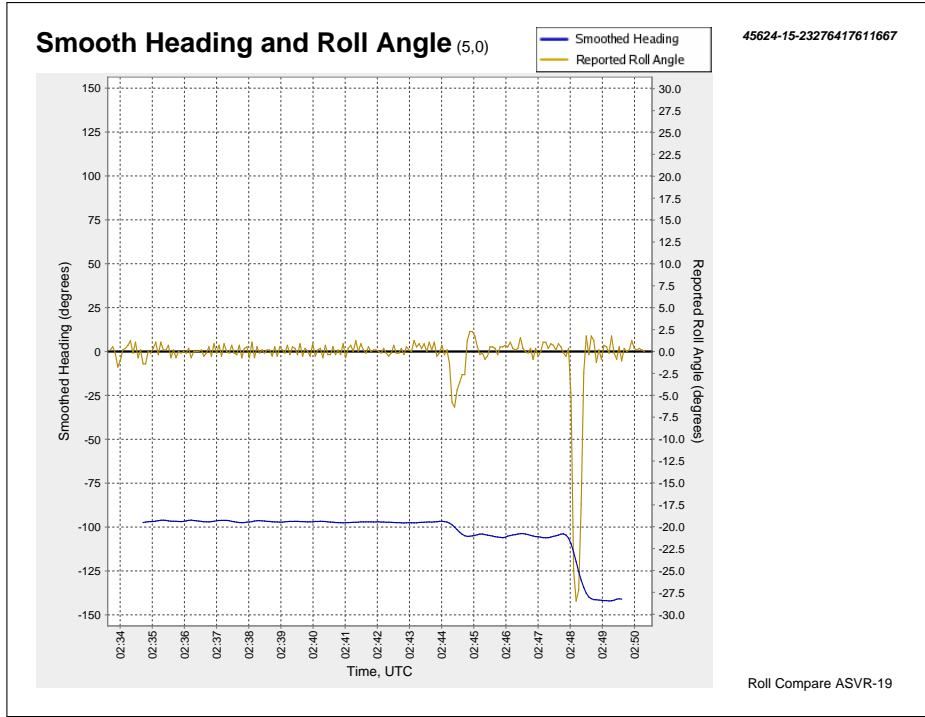
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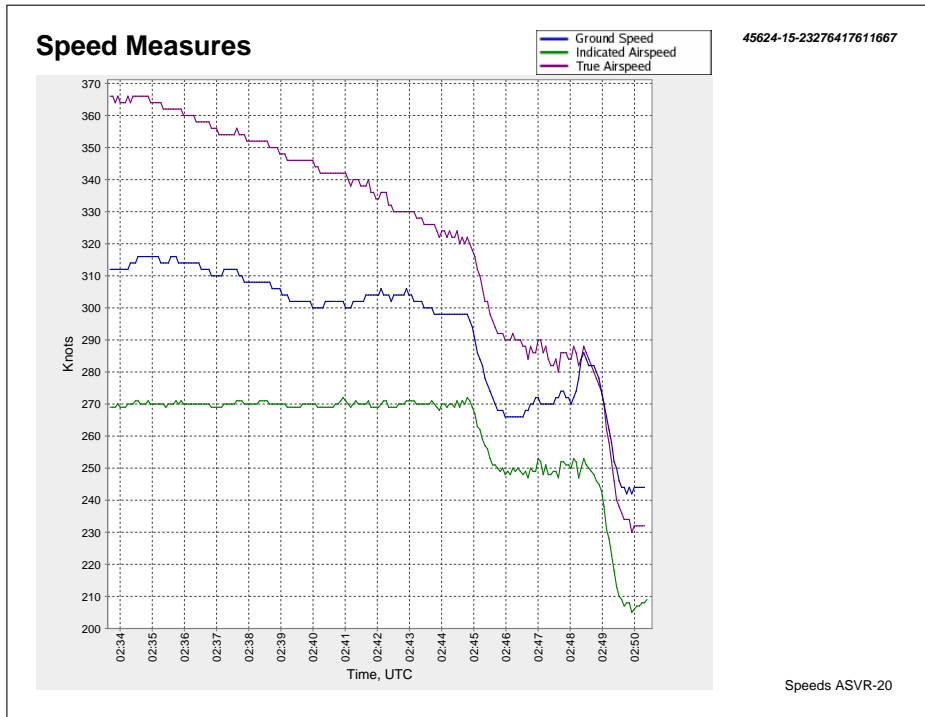
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PDF Scan C.18: ASVR Page 18



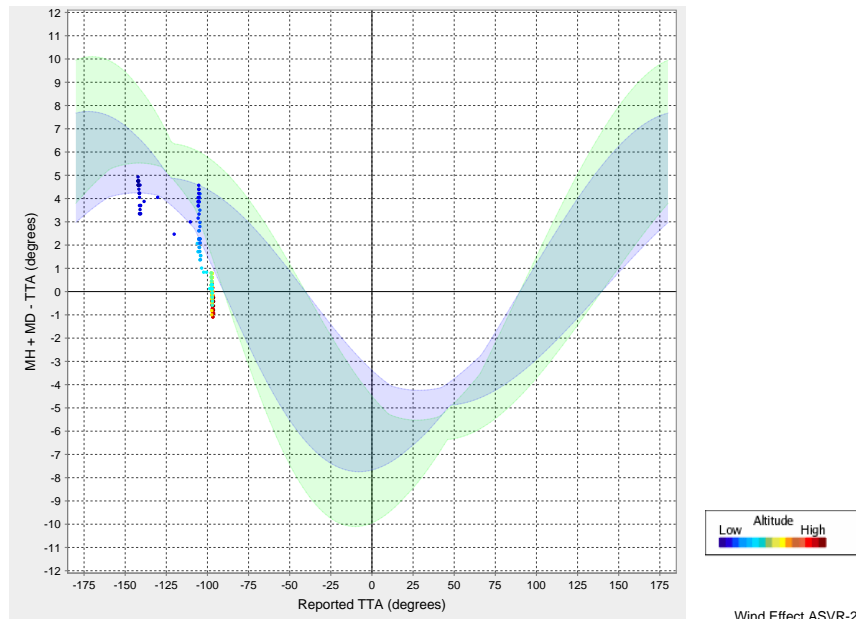
PDF Scan C.19: ASVR Page 19



PDF Scan C.20: ASVR Page 20

Wind Effect

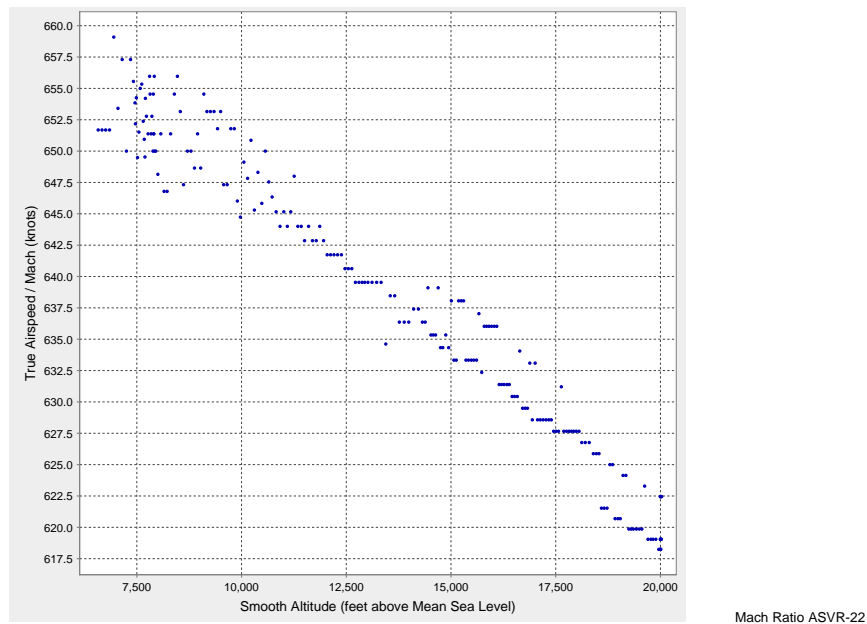
45624-15-23276417611667



PDF Scan C.21: ASVR Page 21

(True Airspeed / Mach) vs Smooth Altitude

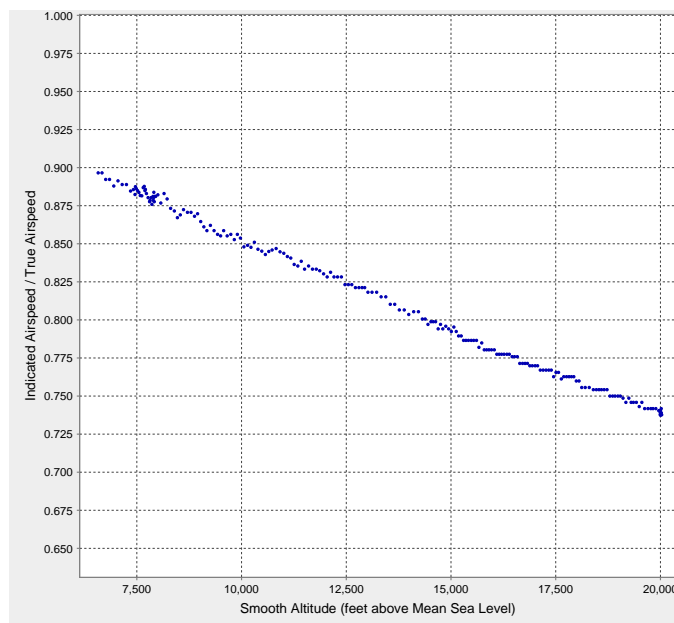
45624-15-23276417611667



PDF Scan C.22: ASVR Page 22

Airspeed Ratio vs Smooth Altitude

45624-15-23276417611667



Airspeed Ratio ASVR-23

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APPENDIX D

CROSS TRACK REPORT (XTR) SAMPLE

The Cross Track Report (XTR) is capable of sorting aircraft over an entire day and collecting those aircraft tracks that display the largest errors in a collection. It was developed for the purpose of quickly pointing out any large errors that exist in the data over a large selection of aircraft. The report shown below is configured to show the 64 tracks with the largest error. An assumption is made that any tracks that this report will highlight that are of interest will exist in the first few tracks. Presenting the first 64, since it conveniently fits on a single page in a readable manner, provides a basis for the error of the population of the set to contrast with the largest errors. Each bar refers to an aircraft track that has an associated Aircraft Specific Validation Report (ASVR).

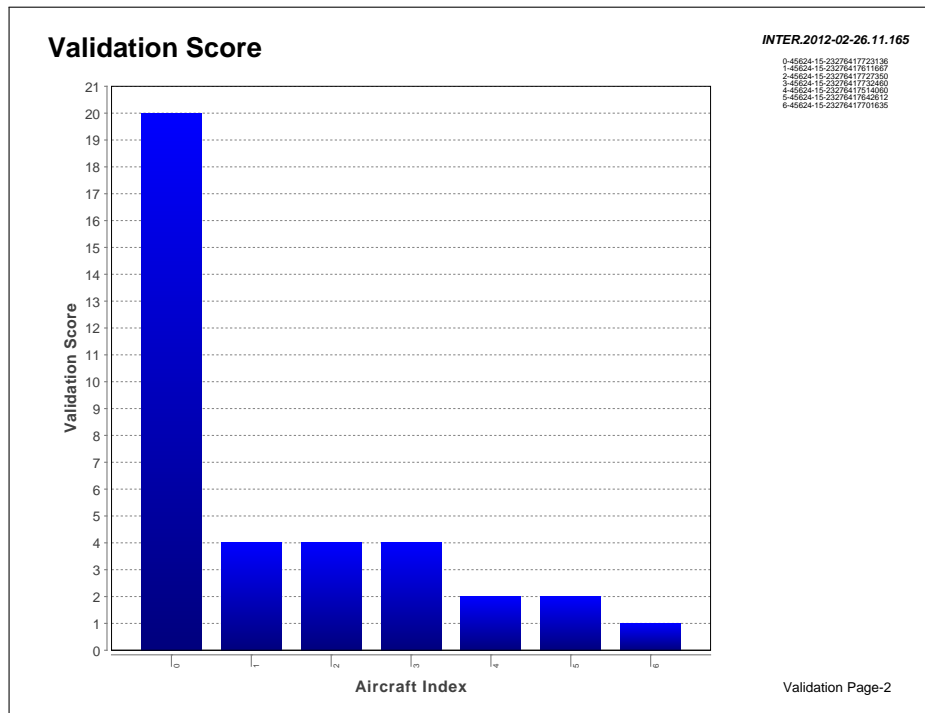
Cross-Track Summary Report

Classification: INTER

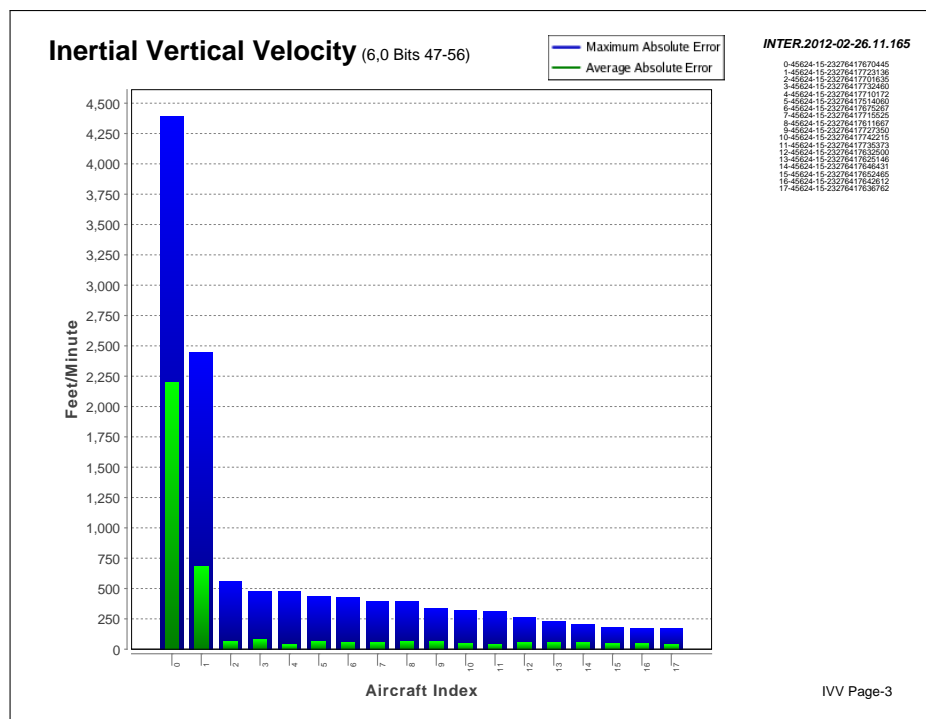
Fremont Valley BI6: Edwards AFB
SAC: 165 - SIC: 11

2012-02-26

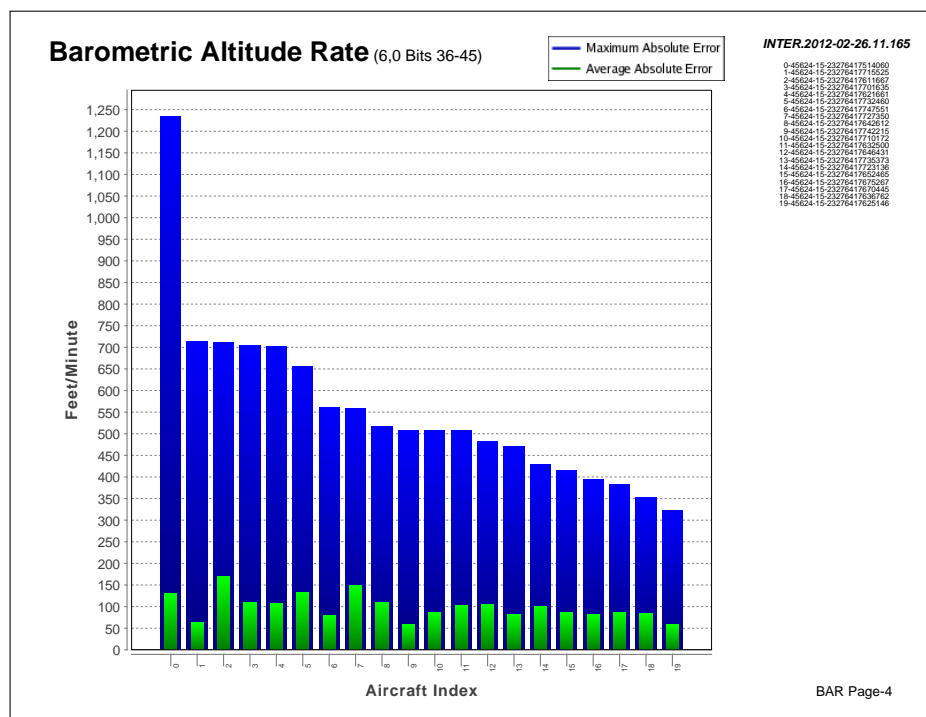
PDF Scan D.1: Cross Track Report Page 1



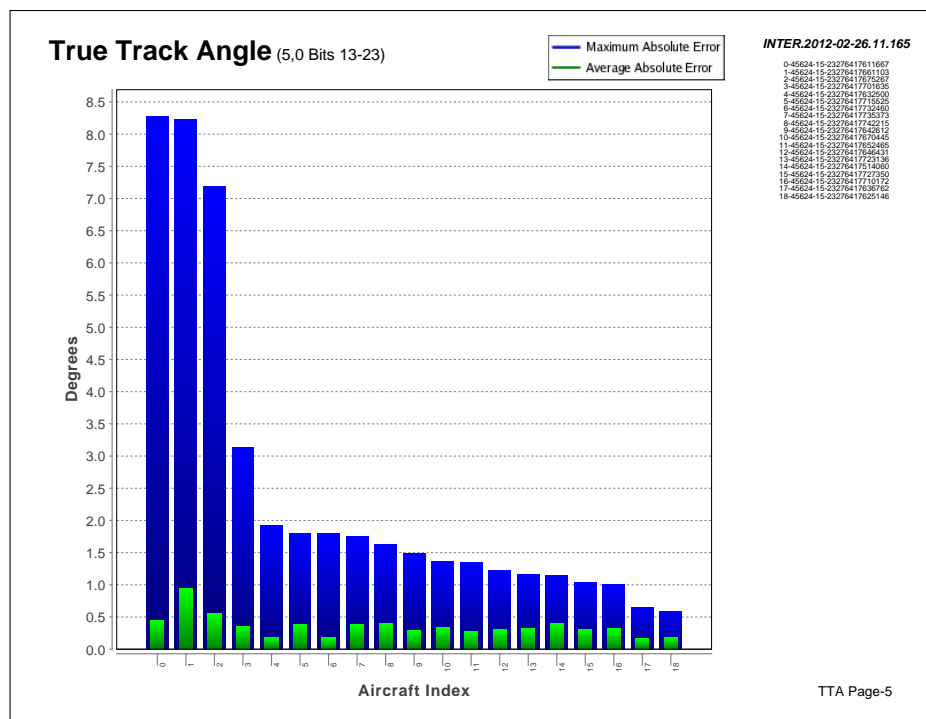
PDF Scan D.2: Cross Track Report Page 2



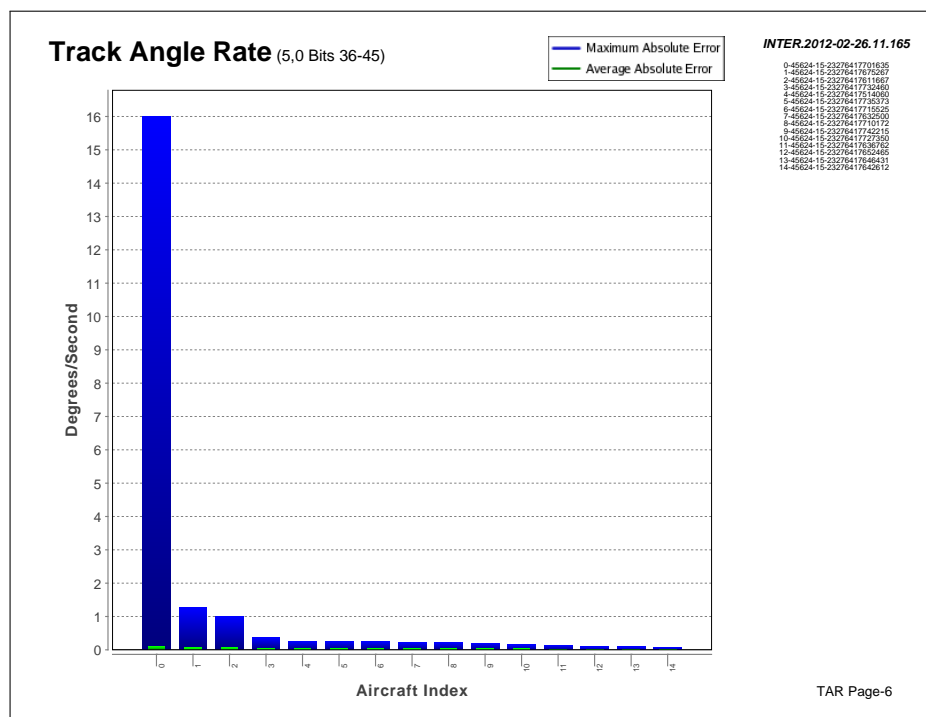
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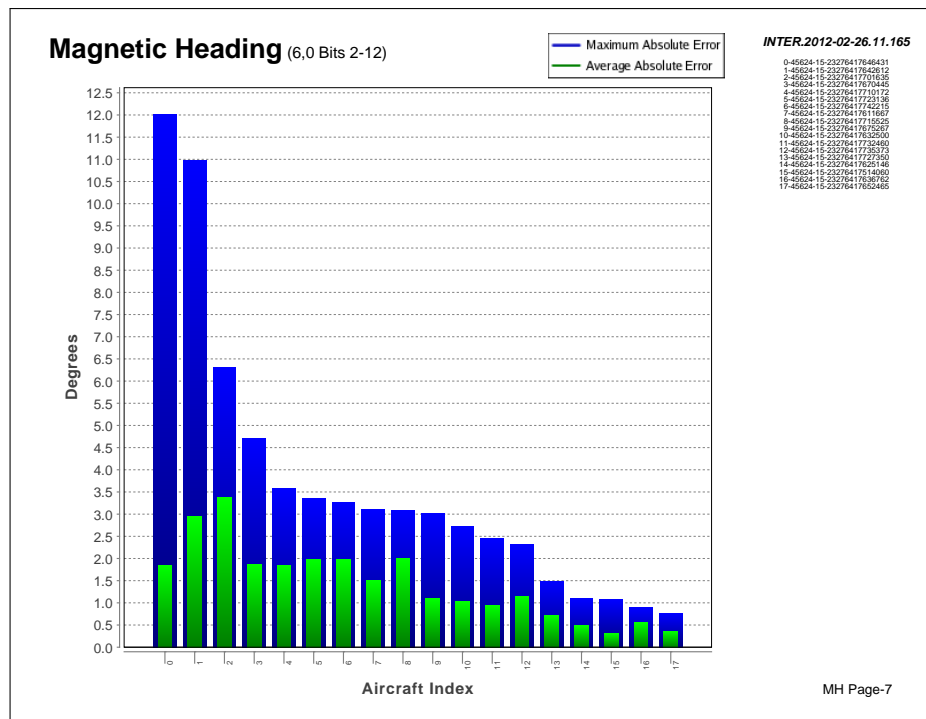
PDF Scan D.4: Cross Track Report Page 4



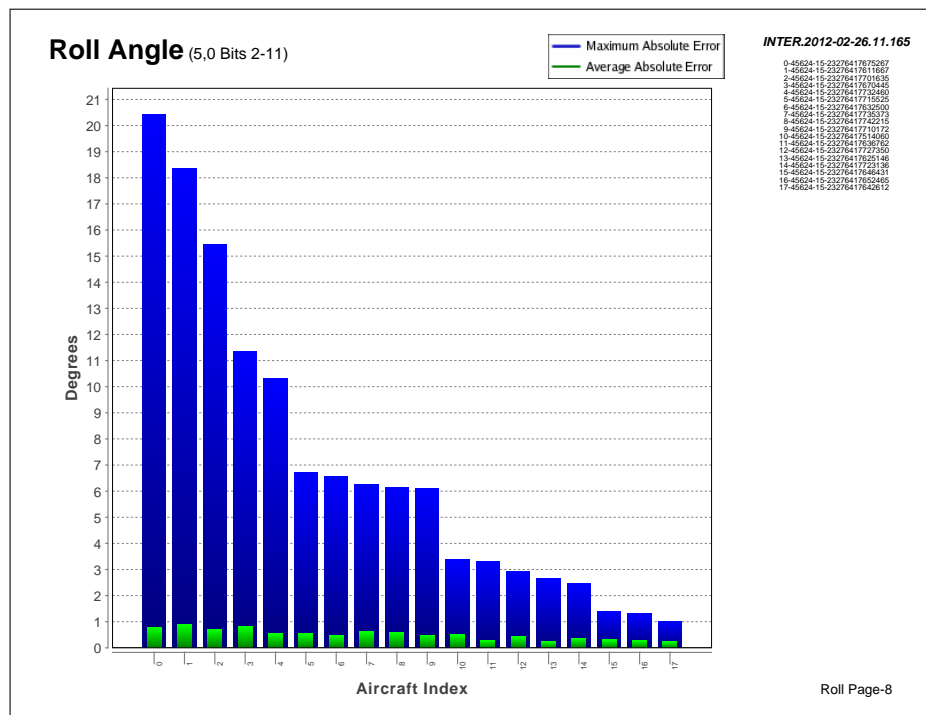
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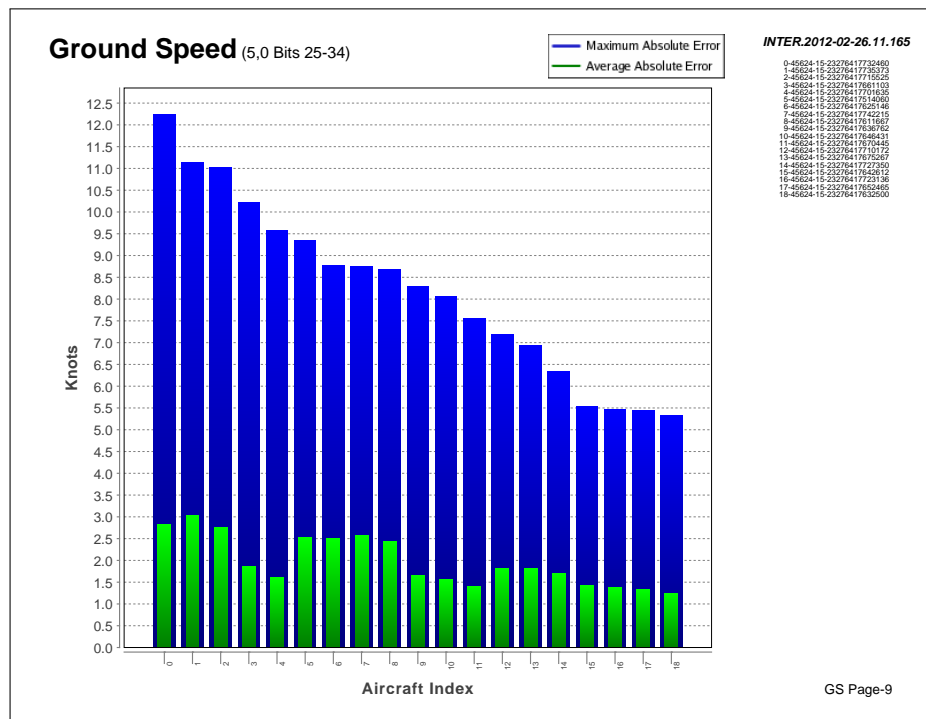
PDF Scan D.6: Cross Track Report Page 6



PDF Scan D.7: Cross Track Report Page 7



PDF Scan D.8: Cross Track Report Page 8



PDF Scan D.9: Cross Track Report Page 9

APPENDIX E

ACRONYM LIST

ADS-B	Automatic Dependent Surveillance – Broadcast
AMSL	above mean sea level
ASV	Aircraft Surveillance Validation
ASVR	Aircraft Specific Validation Report
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
BRSD	Basic Radar Surveillance Data
DAP	Downlinked Aircraft Parameter
EHS	Enhanced Surveillance
ELS	Elementary Surveillance
FAA	Federal Aviation Administration
FMS	Flight Management System
GA	General Aviation
NextGen	Next Generation Air Transportation System
NGA	National Geospatial-Intelligence Agency
PSR	Primary Surveillance Radar
SDP	Surveillance Data Processor
SSR	Secondary Surveillance Radar
USAF	United States Air Force
VS	Validation Score
XTR	Cross Track Report

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14. ABSTRACT This document replaces ATC-337. US Military aircraft operating in civilian airspace are subject to the same avionics equipage requirements as civilian aircraft. To satisfy Air Traffic Control (ATC) mandates, aircraft flying in civilian airspace must be equipped with a Mode S Secondary Surveillance Radar (SSR) transponder that can provide aircraft-derived data when requested by a Mode S SSR. Equipage with a Mode S transponder and the reporting of aircraft call sign is referred to as Elementary Surveillance (ELS). The reporting of aircraft intent and state data is referred to as Enhanced Surveillance (EHS). To meet the European requirements of ELS and EHS, current aircraft data must be maintained in the transponder and provided at the request of a Mode S ground interrogator. These data are used by ATC ground automation systems to provide better predictions of near-term aircraft trajectories than could be obtained from traditional surveillance data, thereby enabling more efficient use of crowded airspace. The United States Air Force (USAF) tasked Lincoln Laboratory to validate that Mode S EHS data from US Military aircraft are in compliance with European mandates. Analysis of US Military aircraft EHS data can be used to identify US Military aircraft with potential compliance shortfalls with respect to the European mandates. This report provides details of the algorithms developed by Lincoln Laboratory to perform this analysis.					
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